

High Spin States in ^{218}Ra

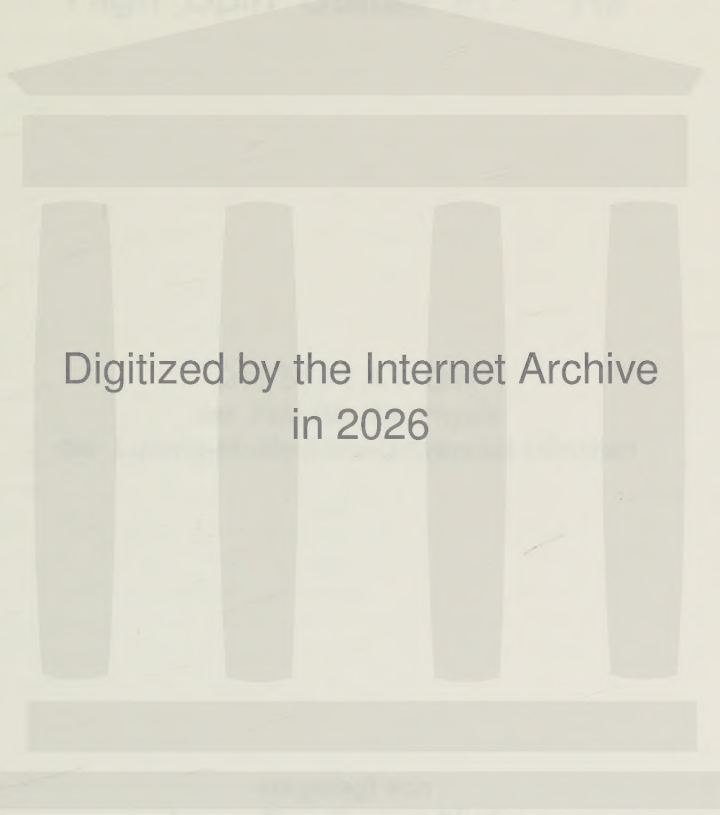
DISSERTATION
der Fakultät für Physik
der Ludwig-Maximilians-Universität München

vorgelegt von
Jorge Fernández Niello
aus Resistencia

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Zusammenfassung

Angeregte Hochspinzustände von ^{218}Ra wurden mit der Reaktion $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ bei Einschußenergien um 69 MeV spektroskopiert. Dieser Kern, mit vier Neutronen und sechs Protonen in den äußersten Schalen, liegt im Übergangsbereich zwischen der abgeschlossenen Neutronenschale $N=126$ und den stark deformierten Kernen der Urangegend. Über die angeregten Zustände von ^{218}Ra gab es bisher keine experimentelle Daten. In den benachbarten Ra-Isotopen sind nur wenige Niveaus aus Untersuchungen des Alphazerfalls bekannt.

Zur Untersuchung dieses Kernes wurden Anregungsfunktionen, Gamma-Gamma- und Röntgen-Gamma-Koinzidenzen, Winkelverteilungen, Lebensdauern mit gepulstem Strahl und Linearpolarisation gemessen. Auf Grund der Meßergebnisse konnten die gefundenen Gamma-Übergänge von ^{218}Ra Zuständen bis zum Spin $I^\pi=17^-$ zugeordnet werden. Im Niveauschema von ^{218}Ra dominieren zwei Banden mit verschiedenen Paritäten. Zwischen beiden Banden treten starke $E1$ -Übergänge auf. Aus den Verzweigungsverhältnissen erhält man für alle $E1$ -Übergänge den gleichen Hinderungsfaktor von 10^{-3} , wenn man annimmt, daß die $B(E2)$ -Werte von ^{218}Ra der allgemeinen Systematik für $E2$ Übergänge folgen.

Die nahezu äquidistanten Energieniveaus der Grundzustandsbande deuten auf einen Vibratorkern hin. Die Energieabstände der untersten Zustände passen gut in die Systematik der geraden geraden Ra-Isotope. Beide Banden, die mit positiver und die mit negativer Parität, lassen sich gut an Hand des IBA Modells (Interacting Boson Approximation) interpretieren. Diese Interpretation deutet auf eine kollektive Struktur der Zustände hin. Die Zustände negativer

Parität können als eine Oktupolvibrationsbande interpretiert werden. Aus der geringen Hinderung der E1-Übergänge folgt, daß in ^{218}Ra oktapoldeformierte Formisomere nicht wahrscheinlich sind.

Abstract

Excited states in ^{218}Ra with spin up to $I^\pi=17^-$ at 3388.5 keV have been identified using the $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ ($E=65\text{--}69$ MeV) reaction and standard gamma-ray techniques. Excitation functions, gamma-gamma and X-ray-gamma coincidences, angular distributions, linear polarization and the gamma-ray emission time in the nanosecond region were measured.

The most interesting result is represented by the appearance of two bands of opposite parities, strongly interconnected through E1 transitions. The structure of these bands is compared with those of other even-even Ra isotopes. The positive- and negative- parity states in ^{218}Ra can be understood in terms of the SU(5) limit of the interacting boson approximation (IBA). An estimate of the hindrance factors of the E1 transitions seems to exclude the existence of shape isomerism in this nucleus.

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I Introduction

With the heavy-ion beams now available, a new field of nuclear research has been opened through the possibility of studying nuclei with very large angular momentum. Investigations of high spin states in nuclei throughout the nuclear table provide an excellent opportunity for exploring new characteristics of nuclear structure. Deformed nuclei at very high spins in the rare-earth region and in the actinides have already been extensively investigated. In the present work, a study of high spin states in a transitional nucleus is reported, namely the radium isotope with mass number $A=218$.

Up to now, there is very little information, both experimental and theoretical, about the structure of nuclei in the transitional region beyond the doubly magic ^{208}Pb . The two extremes of this region are very well known: on the one hand, the nuclear shell model turns out to be adequate to explain the spectra of nuclei close to ^{208}Pb . This model considers the nucleons as independent fermions and gives a description of the nuclear structure in terms of single-particle excitations. Atomic nuclei on the other side of this transitional region, for $A \gtrsim 225$, also show simple and systematic features. These nuclei, the strongly deformed actinides, can be well described by the collective model. With the investigation of the ^{218}Ra isotope presented here, we want to contribute to the understanding of the little explored transitional region between the two studying the change in coupling scheme as more and more nucleons are added to the ^{208}Pb core.

The ^{218}Ra isotope has $N=130$ neutrons and $Z=88$ protons, i.e. it has 6 protons and 4 neutrons outside of the closed shell. The presence of 10 independent particles converts a shell model calculation into a much too complex task, which can not be performed with a reasonable amount of computer time. However, from comparison with other even Ra isotopes, we may expect some important features of nuclear structure taking place in ^{218}Ra . For example, the remarkable low octupole frequencies found in these isotopes, which, as suggested by Bohr and Mottelson (BOH 75, page 561), may be attributed to the introduction of neutrons in the $2g_{7/2}$ orbit. It is striking to observe that just the Ra isotopes show the lowest-energy collective octupole vibrational states (see Fig. 1). This behavior may occur also in ^{218}Ra , where calculations of the potential energy surface (MOE 72) predicted an octupole deformation for the ground state. Therefore, the search for such excitations in ^{218}Ra is one of the interesting aims of this work.

Until now, no excited states of ^{218}Ra were known. A study of the alpha decay of ^{222}Th (VAL 70) revealed only the half-life of the ground state of ^{218}Ra , $t=14\pm 2 \mu\text{sec}$. Our knowledge of other studies of high-spin states in the neighbourhood of this nucleus is limited to the results obtained by Nomura et al. (NOM 75) in ^{216}Ra , Gono et al. (GON 81) in ^{214}Rn and the extensive investigation in the $N=126$ isotones ^{212}Rn , ^{213}Fr and ^{214}Ra done by Horn et al. (HOR 79). In the odd mass nuclei neighbouring ^{218}Ra , only the energy of two excited levels in ^{217}Ra from the alpha decay of ^{221}Th are known and no excited state is known in ^{219}Ra . The spin of the ground state of both odd nuclei is not known. The Ra isotopes with $220\leq A\leq 225$ were studied only through alpha decay of thorium isotopes, with the exception of ^{224}Ra , which was also investigated through the β^+ decay of ^{224}Fr and through the reaction $^{226}\text{Ra}(p,t)^{224}\text{Ra}$. In this nucleus, the ground state band is followed up to the $I^\pi=6^+$ state. High spin states up to $I^\pi=14^+$ are known again in

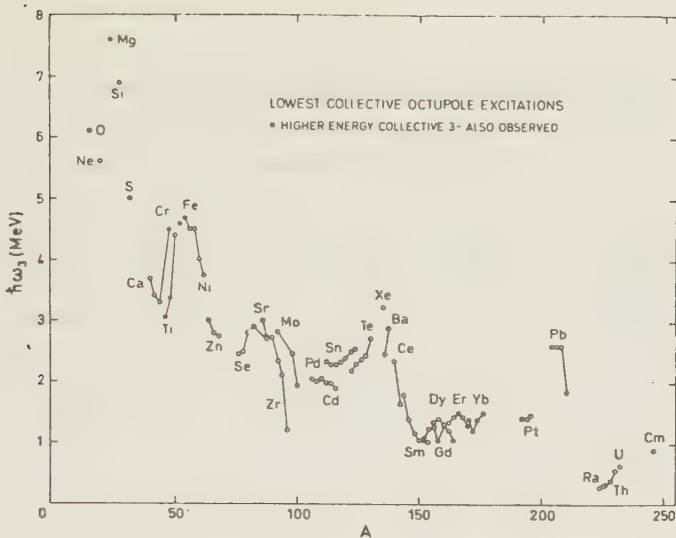


Fig. 1: Systematics of collective octupole vibrational energies. The figure gives the observed excitation energies of the low-energy collective $I^\pi=3^-$ states. Solid circles indicate nuclei in which higher-energy octupole excitations have been identified with a strength not less than half the strength of the excitation that is plotted, taken from BOH 75.

^{226}Ra , which were investigated by Coulomb excitation (ZIM 80).

Fig. 2 shows a section of the chart of nuclides indicating the location of the ^{218}Ra isotope. The experimental work done in this region is also schematically presented in this figure. Nuclei with known excited states are labeled with " α " (if the excited states have been observed in alpha decay experiments) or "h" (if they have been populated through heavy-ion compound nucleus reactions). In the latter case, the highest-spin state known and its parity are also indicated (lower left corner).

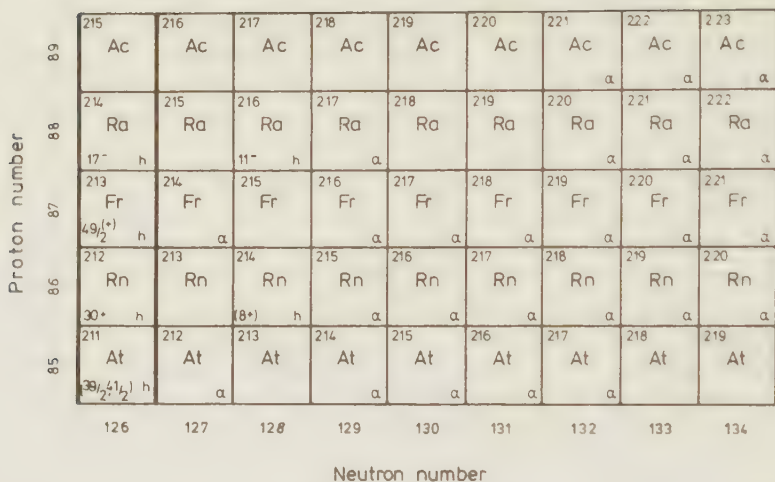


Fig. 2: Location of the ^{218}Ra nucleus in the chart of nuclides. A survey of the experimental works done in this region is also included (see explanations in text).

The alpha-decay experiments limit the study of nuclei to the low spin part of their spectra. The population of high-spin states in this region of the nuclid chart is restricted due to different factors: on the one hand, the heavy-ion compound-nucleus reactions are limited to a small number of cases, because of the few possibilities to choose proper combinations of projectile and target for reaching a specific final nucleus. Moreover, the competition of fission with neutron evaporation can also hinder the production of the desired final nucleus. On the other hand, Coulomb excitation experiments are ruled out since this process is limited to stable or very long-lived nuclei, as in the case of ^{226}Ra .

We investigated high-spin states in ^{218}Ra through the heavy-ion compound-nucleus reaction $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$. The characteristics of this experimental method of in-beam gamma ray spectroscopy are discussed in Chapter II.

We measured the gamma-ray excitation functions, gamma-gamma and X ray-gamma coincidences, the angular distribution of the emitted electromagnetic radiations and their linear polarization. These experiments are described in Chapter III. In this Chapter are also reviewed the experimental setup used (electronic equipments, detectors) and the computer codes for analysis of the collected data.

Chapter IV presents the resulting level scheme of ^{218}Ra . This Chapter presents the arguments for our ordering of the gamma lines, particularly in those cases where the presence of doublets and triplets complicates the construction of the level scheme. A brief review of the most important characteristics of the structure of ^{217}Ra , which were determined simultaneously with the study of ^{218}Ra , is also given in this Chapter.

Comparisons with systematic trends in other even-even Ra isotopes enable us to interpret several features in the structure of ^{218}Ra . The level energies are compared to the variable moment of inertia model and to the interacting boson approximation model in the vibrational limit. Such theoretical considerations on the basis of the obtained data are given in Chapter V.

II Characteristics of the Compound-Nucleus Reaction

II.1. The (HI, xn) Reaction

Reactions induced with heavy ions provide a powerful method to study high-spin states of nuclei. In particular, fusion reactions in heavy mass nuclei and at high bombarding energies produce specific compound nuclei, which, after evaporation of a few neutrons, protons or alphas, deexcite by gamma-ray emission until finally the ground state of the residual nucleus is reached. When only neutrons are evaporated, this is known as a (HI,xn) reaction, where x refers to the number of neutrons emitted. Such reactions were first investigated by Morinaga and Gugelot (MOR 63). A detailed review of the (HI,xn) reactions can be found in MOR 76 and NEW 74. A compound nucleus reaction takes place with a useful cross section (greater than approximately 10 mbarn) only if the incident energy is between 1 to 1.5 times higher than the Coulomb barrier E_{Cb} . For the $^{13}\text{C}+^{208}\text{Pb}$ system, the Coulomb barrier in the laboratory system is given by

$$E_{Cb} = \left\{ 1 + \frac{A_{proj}}{A_{targ}} \right\} 1.02 \frac{Z_{proj}Z_{targ}}{R_C} \approx 60 \text{ MeV}$$

(II.1.)

with

$$R_C \approx \{0.5 + 1.36 (A_{proj}^{1/3} + A_{targ}^{1/3})\} \text{ fm} \quad (\text{NOE 76})$$

where $A_{proj}(targ)$ and $Z_{proj}(targ)$ are the mass number and the charge of the projectile(target), respectively.

If the bombarding energy is chosen appropriately, it is often possible to reach selectively one specific nucleus after the particle emission. This is one of the important advantages of this type of reactions. If the compound nucleus is not too light and not far from the β -stability line, the evaporation of charged particles, such as protons or alphas, is relatively unlikely compared to neutron emission because they must overcome a Coulomb barrier. In the case of protons, for $A \approx 200$, this barrier is about 10 MeV high. Far from the stability line, for neutron deficient nuclei, the neutron binding energies increase and the proton binding energy decrease, and then the proton emission can even predominate.

Fig. 3 shows schematically the deexcitation process for a (HI,xn) reaction in an angular momentum versus excitation energy diagram. The solid line, called the yrast line, connects the states with lowest energy at a certain spin. The shaded region indicates possible initial states of the compound nucleus formed in a heavy-ion reaction, which decays by neutron emission until about one neutron binding energy above the yrast line (dashed line). The nucleus then deexcites by photon emission showing two distinct regions: a continuum composed of a large number of unresolved γ -rays, and a discrete spectrum resulting from the final cascade along the yrast line to the ground state (see, for instance, the pioneering work of Grover and Gilat, GRO 67). In this work the γ -rays of this last region coming from the reaction $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ are studied.

In heavy mass nuclei, in particular in nuclei beyond the double magic ^{208}Pb , heavy-ion reactions at very high bombarding energies can lead to fission, because of the high angular momentum brought into the compound nucleus. The problem of the instability for a rotating nucleus against fission was studied by Cohen, Plasil and Swiatecki (COH 73). In the liquid drop model, the height of the fission barrier

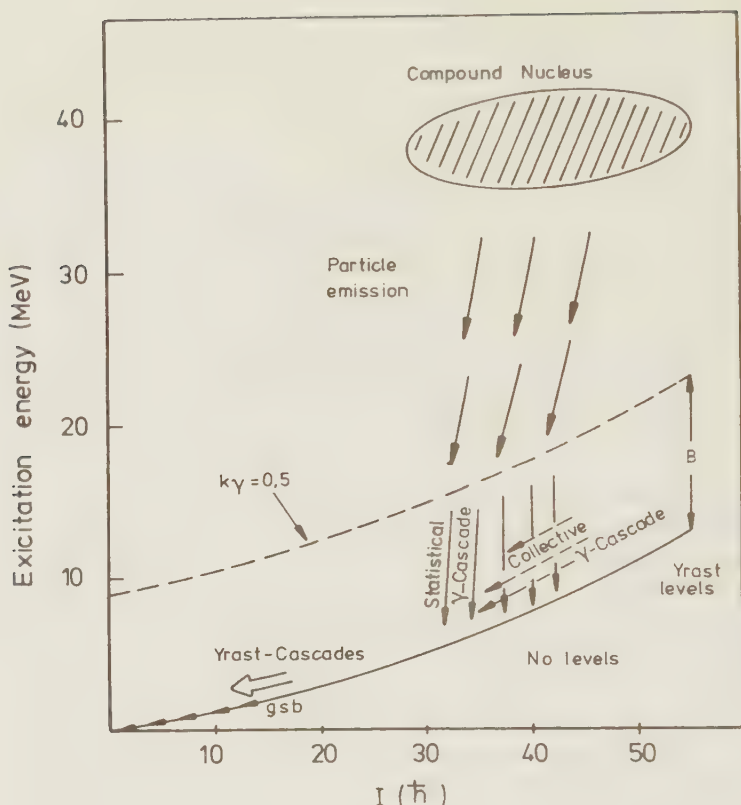


Fig. 3: Energy versus angular momentum plot illustrating the de-excitation processes following heavy-ion compound-nucleus reactions. After particle emission, the nucleus cascades by statistical E1- and collective E2- transitions down to the yrast line, and then to the ground state by a series of E2 transitions along this line. The symbol k denotes the fraction of nuclei de-exciting by gamma-ray emission. If the effect of charged particle emission is neglected, the width B is about one neutron binding energy.

falls off continuously as the angular momentum increases, up to a certain critical spin I_{crit} , where the barrier disappears completely. This means that no nucleus can carry more than a limiting angular momentum. When the fission barrier is higher than 8 MeV (approximately the neutron binding energy of β -stable nuclei), the compound nucleus can survive the possibility of fission in the de-excitation process. Andersson et al. (AND 78) have calculated the angular momentum corresponding to this height of the fission barrier for nuclei in the translead region (see Fig. 4). From this picture, it seems possible to populate high spin states of ^{218}Ra ($N=130$, $Z=88$). This would not be the case in nuclei beyond thorium ($Z=90$), as the fission barrier drops abruptly around this proton number. In this work the fission channel was found not to be important at the incident energies used.

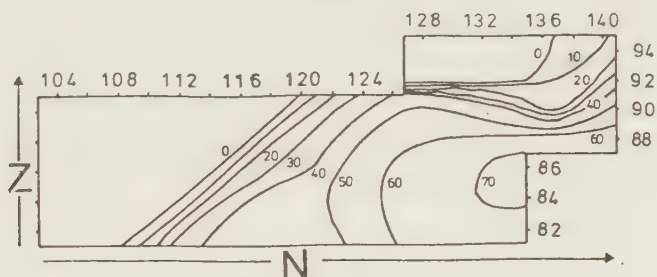


Fig. 4: Contour diagram indicating at which spin the calculated fission barrier is 8 MeV high (from AND 78).

One of the most important characteristics of heavy ion induced reactions is the high mean angular momentum imparted onto the compound nuclei. Classically one can estimate its upper limit L_{max} assuming the capture of the projectile from a grazing collision

$$L_{\max} = .22 R_C \sqrt{\mu (E_{\text{cm}} - E_{\text{cb}})} \quad (\text{II.2.})$$

where E_{cm} is the center of mass bombarding energy and μ is the reduced mass. Assuming a ^{13}C beam with a center of mass energy of 65 MeV, this is the bombarding energy used in the gamma-gamma coincidence experiment (see Section III.3), $L_{\max}$ for the studied reaction is 26 $\hbar$.

The angular momentum of the residual nucleus, before the photon emission, is lower than $L_{\max}$ because the evaporated particles have removed some angular momentum, although the centrifugal barrier inhibits the emission of particles with large angular momentum.

Further, before reaching the discrete region, the gamma-rays cascade down in the continuum, predominantly by statistical dipole transitions, which carry away much energy but only very little angular momentum. In competition with these dipole transitions, there are also collective E2 transitions along bands parallel to the yrast line carrying off angular momentum (LIO 77 and SIM 77). These phenomena cause a reduction of the highest spin $I_{\max}$, which can be observed in the study of the discrete region. For example in the rare-earth nuclei, it has a value of approximately $I_{\max}=0.78 L_{\max}$ (DEL 78).

II.2. Assignment of Multipolarities.

When a target is bombarded with heavy ions, the large orbital angular momentum transferred to the compound nucleus is oriented in the direction perpendicular to the beam. This implies that the compound system is strongly aligned, since the ground state spins of the colliding nuclei are much smaller than the average orbital angular momentum. Each

emitted neutron or gamma-ray carries away only a small amount of angular momentum before the yrast region is reached. Therefore, the primary orientation formed in the collision is only a little more disturbed by these processes.

The degree of orientation of a state having spin J is specified by the population parameters $P_m(J)$ of the angular momentum substates m . In fusion reactions, states with $m=0$ are predominantly populated, yielding an oblate alignment with respect to the beam axis (see MOR 76, page 53), which is therefore chosen as the quantization axis. Yamazaki introduced the experimentally justifiable assumption (YAM 67), that partial alignment may be represented by a Gaussian distribution of the populations of m -states, characterized by a half-width σ .

Because of the alignment of the spin orientation with respect to the beam axis, the γ -rays arising from the decay of an initial state of spin J_i to a final state J_f have an angular distribution of the general form (YAM 67)

$$W(\theta) = \sum_k A_k^{\max} G_k P_k(\cos\theta) \quad (\text{II.3.})$$

Here $A_k^{\max}$ are the theoretical coefficients calculated for maximum alignment, i.e. for the initial state being in the substate $m=0$ (J integral) or $m=1/2$ (J half-integral). They contain the (J_i, J_f, L) geometry of a transition of multipolarity L . The G_k are attenuation coefficients of the alignment, the P_k are the Legendre polynomials, and θ is the angle relative to the quantization axis. If no polarization is observed only terms with k =even occur in this equation and the summation extends up to $k_{\max}$, which is the smaller of $2L$ or $2J_i$.

The angular distribution of gamma radiation can be used to assign multipolarities, since it depends on L . It can, however, not be used to differentiate between electric and magnetic multipoles, since the $A_k^{\max}$ do not contain the parity of the involved states. To remove this deficiency one needs to measure the internal conversion coefficient or the linear polarization of the gamma radiation. An extensive discussion about experimental techniques to measure the internal conversion coefficients is given in HAM 75. The linear polarization experiment, with which the parities of transitions in ^{218}Ra have been determined, will be described in Section III.5.

III Measurements

III.1. Experimental Arrangements

Before discussing in detail the various experiments carried out in this work, we describe briefly some general characteristics of the facilities for gamma spectroscopy that are available at the Munich accelerator laboratory and with which the ^{218}Ra nucleus was studied, such as detectors, electronic equipment, data acquisition systems and computer codes for analysis of the data. A new spectrometer setup for the measurements of the linear polarization will be discussed separately.

III.1.1. Properties and Setup of Detectors

Due to their superior energy resolution compared to scintillation crystals, semiconductor detectors have become a standard tool for the study of gamma radiation from discrete transitions. In the course of these experiments two types of such spectrometers have been used: pure Ge planar detectors and true coaxial Lithium drifted Germanium (Ge(Li)) detectors. The first ones have better energy resolution than coaxial Ge(Li) detectors, but because of their small sensitive volume they have a good detection efficiency only up to approximately 500 keV. The planar geometry provides uniform fields, yielding a pulse-rise characteristic well suited for fast-timing experiments. On the other hand, the large sensitive volume of the coaxial

detectors makes possible the detection of gamma-rays with a good efficiency for energies above 100 keV.

In order to reduce the detection efficiency at low gamma energy, thus avoiding large dead times coming from the high counting rate of the X rays, absorbers of copper (0.5 mm thin) and tantalum (0.3 mm thin) were placed in front of the planar and the coaxial detectors, respectively. The characteristics of the detectors used in this work are summarized in Table I.

The spectra obtained in-beam show a background due to radiation coming from decay products, to neutrons reacting in the detector and to Compton-scattered radiation, especially the one arising from neutron interactions with the target support or the scattering chamber. These events are generally of low multiplicity. To discriminate against this unwanted background which could make the detection of weak transitions difficult, a multiplicity filter composed of NaI detectors has been used. Such a system, which requires coincidence events between the NaI and the Ge(Li), reduces particularly the low multiplicity events. Events with high multiplicity, which are expected to come from the nucleus to be studied, are not severely reduced, because of the high detection efficiency of the NaI detectors.

The different measurements were performed using a cylindrical scattering chamber of 100 mm diameter. It has a 0.2 mm thin Al window providing constant transmission between 30° and 150° with respect to the beam axis. After having been defined by a slit of 3 mm diameter placed 30 cm before the target position, the beam passed through the scattering chamber and was stopped in a Faraday cup, approximately 4 m behind the target.

Table I: Characteristics of the detectors used in the various experiments.

Geometry	Volume	Efficiency ¹	FWHM ²	Experiment
Planar Ge	10 cm ³		800 eV	Excitation functions. X ray- γ coincidences. Lifetime with pulsed beam.
Planar Ge	36.1 cm ³		690 eV	Linear polarization.
True coaxial ³ Ge(Li)	120 cm ³	24%	2.0 keV	X- γ and γ - γ coincidences. Angular distributions. Linear polarization.
Wrap coaxial Ge(Li)	60 cm ³	11%	2.2 keV	Excitation functions. Angular distributions.

¹ The efficiencies are specified relative to a 3"x3" NaI, for radiation of an energy of 1.333 MeV emitted from a source at a distance of 25 cm.

² The FWHM are given for 122 keV and 1.33 MeV for the planar and coaxial detectors, respectively.

³ The coincidence measurements were performed using two detectors of this kind with almost identical characteristics; in the linear polarization measurements, four detectors of this kind were used.

III.1.2. Electronic Setup and Data-Acquisition System

The electronic setup used in this work is standard for gamma spectroscopy. As an example, the block diagram in Fig. 5 illustrates the electronic setup for the coincidence measurement described in Section III.3.

It is worth mentioning typical values of the counting rate and the dead time during the experiments. The determination of dead times, which depends on the counting rate, is important in measurements where the gamma intensities must be determined very accurately. This is the case, for example, in the angular distribution measurement, in which the intensities of spectra taken at different angles must be compared with each other. The counting rates of these spectra are influenced by the angular distribution of the gamma radiation and the neutron background, which is stronger at forward angles. Therefore, the dead times of the measurements taken at different angles are not the same, and they have to be measured for a proper normalization of these spectra.

Bombarding a 1.5 mg/cm^2 ^{208}Pb target with a ^{13}C beam of 10 particle-nA, the counting rate measured with the Restorer Busy Output of the amplifier was about 15 kHz for a target-detector distance of about 20 cm. The corresponding dead time, with the shaping time constant of the amplifier set on 2 μsec , was estimated to be roughly 10%. (Actually this risetime setting is a compromise between a reasonable dead-time and the energy resolution of the whole system; a smaller Shaping Time Constant would decrease the dead time, but the energy resolution would become worse). A contribution to the dead time also comes from the Analog-to-Digital Converter (ADC): the average time during which the ADC is busy is approximately 10 μsec . The single

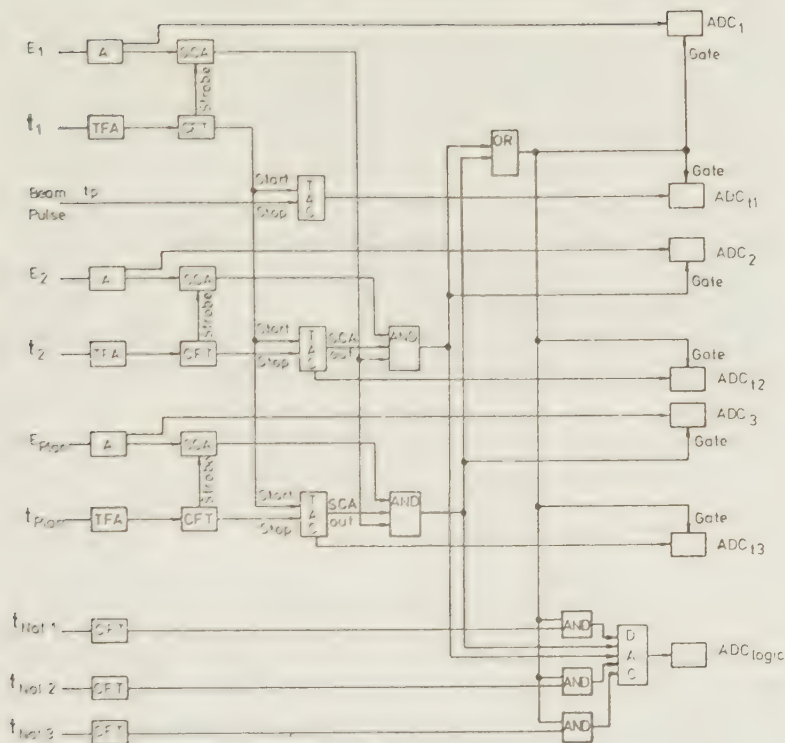


Fig. 5: Block diagram of the electronic setup used in the measurement of the gamma-gamma coincidence (see Section III.3.1.). A= amplifier, SCA= single channel analyzer, TFA= timing-filter amplifier, CFT= constant-fraction trigger, TAC= time-to-amplitude converter, DAC= digital-to-analog converter.

spectra were accumulated in a PDP15, which accepts roughly a 700 kHz counting rate, without introducing dead time. The method used to correct for the dead time is explained in

Section III.2.

The coincident counting rate between two Ge(Li) detectors with similar experimental arrangement was about 500 Hz. For the coincidence measurements the PDP8/PDP10 on-line system of the accelerator laboratory was used. The events were accumulated in the memory at the PDP8 serving as a buffer, were then transferred in groups to the PDP10, written on magnetic tapes and accumulated in the on-line spectra. For the above mentioned counting rate, the dead time of ADC is negligible and only a busy PDP10 introduces dead time. The largest amount of dead time comes from the amplifiers and depends on the singles counting rate.

III.1.3. Analysis of Data

The data was analyzed off-line using the PDP10 computer of the accelerator laboratory and the PDP15 computer of the University of Munich. The gamma spectra were analyzed using the computer code GASPAN (RIE 77). This program, which performs an automatic data analysis, determines the locations and areas of the peaks in the spectra by fitting Gaussian line shapes with the option of a low energy tail to the data points and a polynomial to the background. The fitting uses a least squares procedure with an iterative minimization method. The high line density in our gamma spectra imposes a special problem for an automatic peak fitting program. The fit, however, can be substantially improved and speeded up by specifying as input parameters an appropriate degree for the background polynomial as well as the boundaries of the fit region.

The spectra obtained with detectors located at forward angles show gamma lines having a high-energy tail produced by Doppler shift. The computer code PEP was used to analyze such spectra. This code has the possibility of fitting to the lines exponential tails on both sides of the Gaussian peak.

The theoretical angular distributions and angular correlations of the gamma radiation were obtained by running the computer code ANGDIS (RIE 74). Besides the coefficients A_2 and A_4 (cf. formula II.3.), it calculates a matrix of correlation intensities, which have to be taken into account by evaluating the gamma intensities in the coincidence experiment. Both, the coefficients A_2 and A_4 and the correlation matrix are calculated as function of the spin sequence, population parameters, multipole mixing ratio of the transitions, and detection angles.

A particular background subtraction procedure applied in the analysis of the gamma-gamma coincidence measurements will be explained in section III.3.1.

The energy scale of the spectra was calibrated with ^{57}Co , ^{60}Co , ^{133}Ba , ^{152}Eu and ^{182}Ta sources. The relative detection efficiencies for singles as well as for gamma-gamma coincidence spectra were obtained from spectra taken with the sources mounted at the target position. The energies and relative intensities of the gamma-rays from the sources were taken from LED 78.

III.2. Excitation Functions

In heavy-ion compound-nucleus reactions followed by the emission of neutrons, the maxima of the cross sections of the different exit channels are very well separated as a function of the beam energy. Therefore, the measurement of the excitation functions for each gamma-ray, namely the variation of the peak intensity with the bombarding energy, allows an almost certain assignment of the nuclide from which the line originates.

An empirical expression to estimate the optimum incident energy of the excitation function for the xn-channel was given by Newton (NEW 74):

$$E_{\text{opt}}(x) = (1 + \frac{A_{\text{proj}}}{A_{\text{targ}}}) (-Q_x + \alpha x) \quad (\text{III.1.})$$

where x denotes the number of evaporated neutrons, Q_x is the Q value for the reaction, and α is approximately 6 MeV, according to a compilation of experimental cross sections in the mass region $100 \leq A \leq 150$ by Neubert (NEU 71).

A similar estimate for the mass region $215 \leq A \leq 225$, with experimental cross sections taken from VAL 68, TOR 68, VAL 70, TOR 70, ESK 72 and NOM 72, yields a value of $\alpha = 3.5$ MeV. With this value of α , the maximum of the cross section for the 3n-, 4n-, and 5n channels are at 64 MeV, 75 MeV and 85 MeV respectively. With the available voltage at the Munich MP tandem accelerator, a carbon beam with energies up to 84 MeV could be supplied, so that excitation function measurements involving those three channels could be performed.

The experiment was carried out by irradiating a self-supporting ^{208}Pb target with a pulsed beam at different energies between 60 and 82 MeV. The target was 1.3 mg/cm^2 thick and enriched to 97%. The γ -rays were detected with a Ge(Li) detector and a planar Ge detector; a $5'' \times 5''$ NaI was also used in this measurement as a multiplicity filter. The detectors were placed at a distance of 20 cm from the target, at 90° with respect to the beam axis. This has the advantage, that the spectra do not suffer from Doppler shifts. Prompt and delayed singles spectra from both detectors and gamma-gamma coincidence spectra with the NaI detector were accumulated. The normalization of the spectra at the different bombarding energies was done with the integrated beam current measured at the Faraday cup. Correction for dead-time was done by enabling the beam current scalers only when the amplifier and the ADC of the respective detector were not busy.

According to the excitation curves, the detected γ -rays could be classified into three groups: The highest, involving the known ^{216}Ra gamma transitions (5n channel), is seen at bombarding energies in excess of about 75 MeV. Another group of γ -rays, two of which belong to the transitions between known excited levels of ^{217}Ra (4n channel), shows a peak in its excitation curve at 75 MeV. And finally a third group of lines, with their excitation curves peaking at 67 MeV, was assigned to the ($^{13}\text{C}, 3n\gamma$) reaction channel. A measurement of X ray- γ coincidences confirmed the $Z=88$ assignment. It was also observed that reactions ($^{13}\text{C}, xn\alpha\gamma$) involving alpha particle emission are about two orders of magnitude less intense than the corresponding neutron evaporation channels. In Fig. 6 the excitation functions for representative γ -rays from the ($^{13}\text{C}, 3n\gamma$), ($^{13}\text{C}, 4n\gamma$) and ($^{13}\text{C}, 5n\gamma$) reactions are shown. Gamma-ray spectra taken with the Ge(Li) detector in coincidence with the NaI one at 65 MeV, 74 MeV and 83 MeV beam energies are presented in Fig. 7a), b) and c),

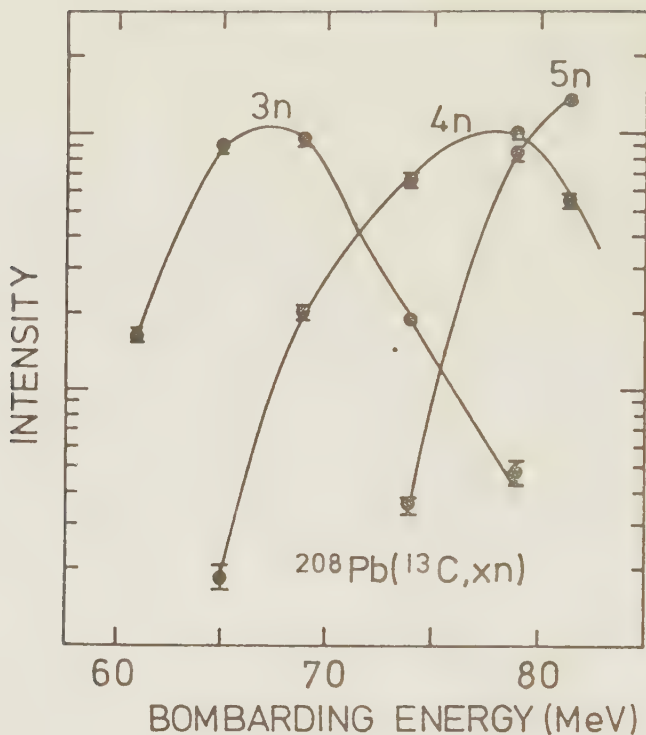


Fig. 6: Excitation functions of the xn - channels following the $^{13}\text{C}+^{208}\text{Pb}$ compound nuclear reaction at beam energies $E=60-83$ MeV. The curves represent the yields of the most intense γ -rays in each channel: 3n: 388.8 keV for ^{218}Ra ; 4n: 330.4 keV for ^{217}Ra ; 5n: 687.9 keV for ^{216}Ra .

Fig. 7: (next page) Gamma-ray spectra taken with a Ge(Li) detector in coincidence with a 5"x5" NaI following the reaction $^{13}\text{C}+^{208}\text{Pb}$ at $E_{\text{beam}}=65$ MeV, 74 MeV and 83 MeV. The lines labeled with their energies are transitions in ^{218}Ra ($E_{\text{beam}}=65$ MeV), ^{217}Ra ($E_{\text{beam}}=74$ MeV) and ^{216}Ra ($E_{\text{beam}}=83$ MeV).

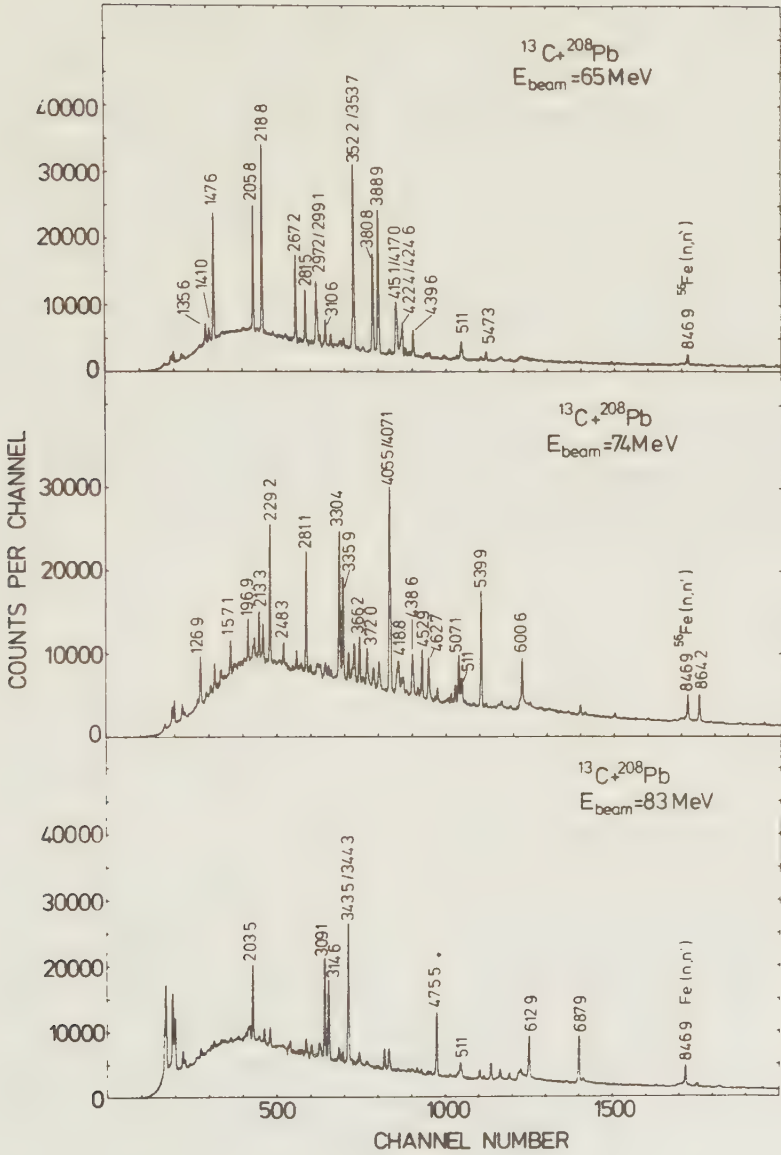


Fig. 7

respectively.

The cross sections of the exit channels for the reaction $^{13}\text{C}+^{208}\text{Pb}$ were calculated using the evaporation code ALICE (BLA 66), showing that the neutron evaporation channels are the predominant ones. The bombarding energies corresponding to the maximum cross section calculated with this program in "all defaults" mode are shifted by 7 MeV relative to the experimental ones. This difference between calculation and experiment was also found when other experimental cross sections in the mass region $215 \leq A \leq 225$ (taken from the references above quoted) were calculated with this code. Recently, Lister et al. (LIS 81) have reported a similar shift between a calculation using the evaporation code CASCADE (PUH 77) and the experimental cross sections for the $^{16}\text{O}+^{144}\text{Sm}$ reaction. These differences must probably be attributed to an underestimate of the γ -decay probability at high spin.

III.3. Coincidence Measurements

The gamma-gamma coincidence experiments provided the basis for the construction of the level scheme. This measurement was carried out using a pulsed beam of ^{13}C at 69 MeV, i.e. 2 MeV higher than the maximum for the $3n$ reaction channel, in order to enhance the population of states with higher spins in ^{218}Ra (cf. Section II.1.), even though the production of ^{217}Ra ($4n$ channel) became significant: for the intensity ratio of the strongest line in ^{217}Ra (330 keV) and in ^{218}Ra (352 keV) we obtained 0.38 at this energy.

The data was accumulated with an array of two coaxial Ge(Li) detectors (detectors 1,2) with similar efficiency and energy resolution, one planar Ge detector (detector 3), two 4"x4" and one 5"x5" NaI counters (see Fig. 8). The particular arrangement of the detectors, placed at different angles with respect to the beam axis was chosen in order to have a rough information about the multipolarity of the transitions in addition to the coincidence intensity information.

Seven parameters were simultaneously recorded: the pulse heights recorded in detectors 1,2,3, the time between detector 1 and beam pulse, the time between detector 1 and detectors 2,3, and the number of NaI counters fired. From these data two 2048x2048 coincidence matrices were created (detector 1 vs detector 2 and detector 1 vs planar). A large number of runs were taken, totalling about 10^8 coincident events between detector 1 and detector 2. This high statistics is very important in trying to identify transitions from weakly populated states of the investigated nuclei. The quality of the data can be seen from the counting rate that remains in a coincident spectrum after a background subtraction: if gates are set on strong lines, the spectra contain approximately 450 000 events. Those gated on weak lines (having roughly 20 times less intensity than the $2^+ \rightarrow 0^+$ transition) include approximately 25 000 events. The total coincident spectrum corresponding to Ge(Li) 1 is shown in Fig. 9.

A comparison between coincidence spectra with different requirements of multiplicity (i.e. coincidence spectra where none of the NaI fired to those where one or two NaI fired) does not reveal any significant difference in the relative intensity of a particular line. This means that the intensities of lines from activities, expected having low multiplicity, are not appreciable. The analysis of the coincidence measurement using the planar detector yields the

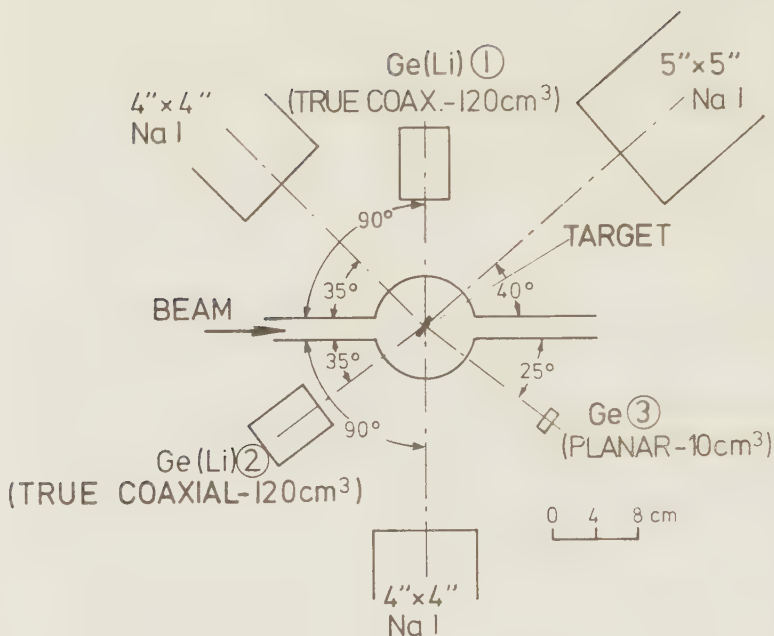


Fig. 8: Schematic diagram of the experimental arrangement used in the γ - γ coincidence measurement. The target was a self-supporting ^{208}Pb foil of 1.3 mg/cm² thickness.

same result. After setting gates on the X-rays and subtracting the background it could be proved that, besides the neutron evaporation, other exit channels are unimportant.

A subtraction of chance coincidences was not necessary in this measurement, since the background in the time spectra is negligible compared to the prompt peak. It turns out that the 511 keV line, which is clearly the most

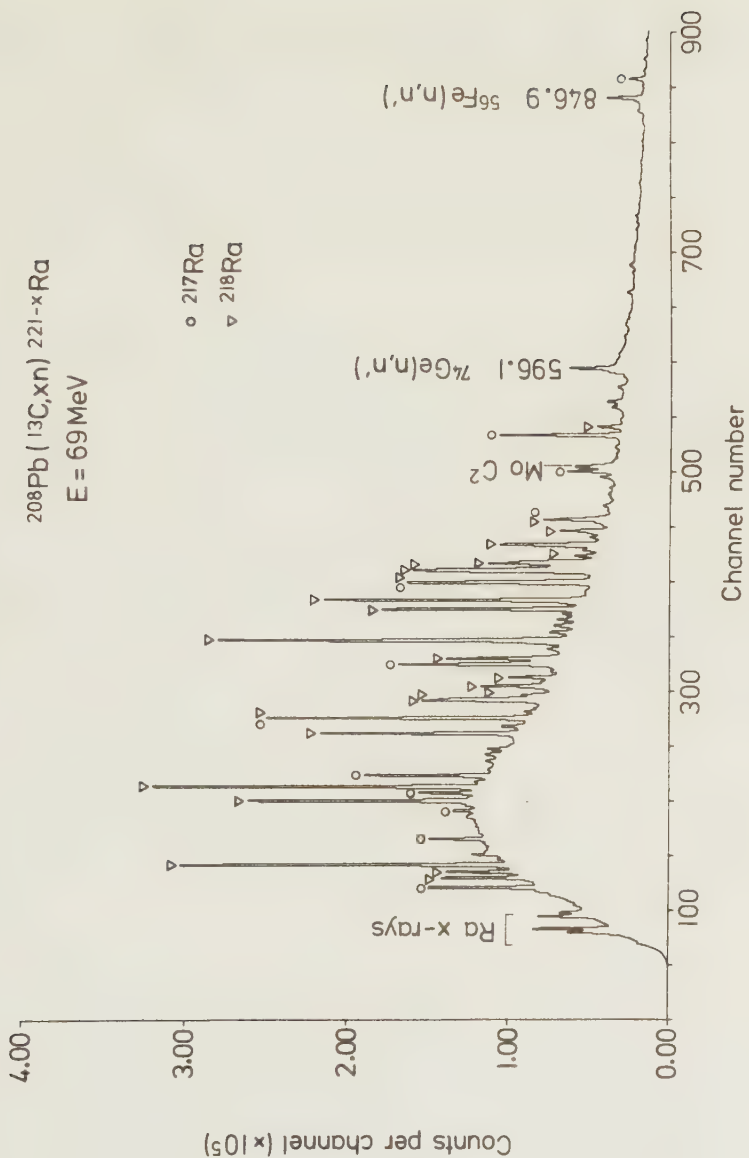


Fig. 9: Total coincident spectrum of the reaction
 $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ at $E_{\text{beam}} = 69 \text{ MeV}$.

prominent line when a gate is set on the background of the time spectra, disappears almost completely in the coincidence spectra.

III.3.1. Analysis of the Coincidence Measurements

The first step in analyzing the coincidence data consists in subtracting accidental events in order to obtain spectra without contributions of background coincidences. This facilitates an unambiguous determination of coincident lines.

Due to the high density of lines in the spectra (it is almost impossible to find regions free of lines), the usual procedures for background subtraction were not applicable. The method used here, developed by F. Riess, will be briefly outlined below.

Each axis of a coincidence matrix corresponds to the gamma energies registered in a particular detector. Hence, to each channel of one axis (detector) corresponds a coincident spectrum with the whole energy-range of the other detector. In the following, such spectra will be called "cut-spectra".

A coincidence matrix is shown schematically in Fig. 10.a. In this example, E_a and $E_{a'}$ are the energies of two coincident lines. The third line (with energy E_b) is not in coincidence with the first two. The peaks resulting from the coincidence between E_a and $E_{a'}$ (lying at the coordinates $(E_a, E_{a'})$ and $(E_{a'}, E_a)$, respectively) are marked with an arrow. To each of the three energies corresponds a ridge, which is composed of true coincidences in which the total

energy of one gamma ray is deposited in one of the detectors while the other gamma ray is only partially absorbed and of the statistical gamma-ray continuum.

For all channels along one axis of the matrix, the corresponding cut-spectra were analyzed with the computer code GASPAN. The peak areas obtained from this analysis are again sorted in the form of a matrix (see Fig. 10.b).

At the point where two ridges cross (for example, at the coordinate (E_a, E_a) in Fig. 10.a) there is a chance peak. The elevation of such "ridge crossing" is about the same as the height of the ridge in the neighbouring "plane part" of the matrix. On the other hand, the real coincident peaks are much higher because of the additional contribution of the actual coincidence intensity (total absorption of E_a and E_a'). Therefore, when a cut spectrum which contains a peak of the type (E_a, E_a) or (E_a, E_b) is analyzed with the GASPAN program, an intensity at this place will be found, which is similar to those in the cut spectrum of the neighbouring channels. In this way, considering only intensities (i.e. peak minus background), only the peaks which are really in coincidence survive.

Therefore, a subsequent analysis with the GASPAN program on the new matrix (this time along the other axis) yields true coincident intensities, since the new generated cut-spectra are free of background coincidences.

An additional feature contributing to the quality of the data lies in the resolution obtained in this measurement. A gamma transition of about 300 keV has in the coaxial detectors a FWHM better than 2 keV. The calibration of the energy scale in the coincident matrix was chosen so that one channel corresponds to one keV. Thus, each cut-spectrum has a width of 1 keV, i.e. it contains events of the whole energy range of one detector which are in

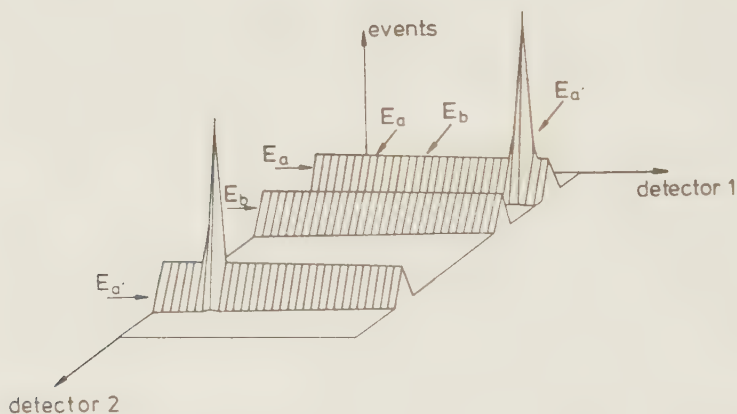
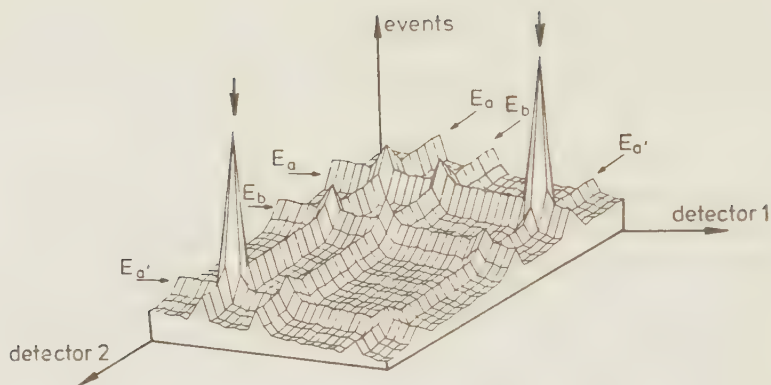


Fig. 10: Schematic representation of a coincidence matrix. E_a and $E_{a'}$ are the energies of two coincident lines. E_b is not in coincidence with any of these lines, (Fig. 10 a). For every channel of detector 1 the corresponding energy spectrum of detector 2 was analyzed with the GASPAN program. The matrix in Fig. 10 b) represents the peak areas of the analyzed spectra.

coincidence within an energy range $\Delta E=1$ keV of the other detector. In this way, it was possible to resolve even doublets like the 297-299 keV, the 352-353 keV and the 422-424 keV one.

III.4. Angular Distribution Measurements

In this experiment, the ^{218}Ra nucleus was produced by bombarding a self supporting 1.0 mg/cm^2 ^{208}Pb target by 65 and 69 MeV ^{13}C beams. At a beam energy of 65 MeV, other reaction channels are weak, which facilitates the analysis of the spectra. However, since the intensities of transitions occurring at high spin are very weak at this bombarding energy, also a measurement with a beam energy of 69 MeV was performed.

The measurement of the angular distributions of the gamma radiation was carried out by taking spectra at angles 30° , 39° , 48° , 56° , 67° and 90° with respect to the beam direction. To normalize the spectra taken at different angles, a second detector was held fixed at 70° on the other side of the beam line and used as a monitor. Both detectors were placed at a distance of 20 cm from the target.

After dead-time correction, the normalized peak intensities obtained from these spectra were fitted to a polynomial expansion (cf. formula II.3.). When plotted against $\cos^2\theta$, the yields of dipole transitions should lie on a straight line ($P_2 \propto \cos^2\theta$) and the yields of quadrupole

transitions on a parabola ($P_4 \propto \cos^4 \theta$). These characteristics are exhibited in Fig. 11.a and 11.b, which show some angular distributions of prominent quadrupole and dipole transitions from ^{218}Ra , respectively. In this picture, the solid lines represent the theoretical values for the intensities for dipole and quadrupole transitions calculated with the ANGDIS program. A Gaussian population distribution of width $\sigma=2.8$ was used in the calculations, which was determined from the angular distributions of the stretched E2 transitions.

The parameters extracted from the fit, A_2^{exp} and A_4^{exp} , are listed in Table II. From these parameters the quadrupole-dipole mixing ratios

$$\delta = \frac{\langle J_i \parallel L=2 \parallel J_f \rangle}{\langle J_i \parallel L=1 \parallel J_f \rangle}$$

were determined. The method used for the actual calculation of δ was suggested by Arns and Wiedenbeck (ARN 58), where the values of A_2^{max} and A_4^{max} are plotted as functions of the quantity $Q = \delta^2 / (1 + \delta^2)$. Fig. 12 shows such plots for the 206 keV and 219 keV dipole transitions for the case $J_i = J_f + 1$. Another possibility for these dipole transitions, namely for $J_i = J_f$, are not compatible with the experimental values of A_2 and A_4 . The values of $A_K^{\text{theor}} = A_K^{\text{max}} G_K$ as function of Q were calculated with the ANGDIS program, using a Gaussian population distribution of width $\sigma=2.8$ for the initial state. It can be seen, that the dipole-like transitions are consistent with pure $L=1$ (i.e. their deltas are compatible with zero). This is a suggestive indication that these lines are of electric type, see discussion in Section VI.1. Their true parities were investigated by determining the linear polarization of the transition.

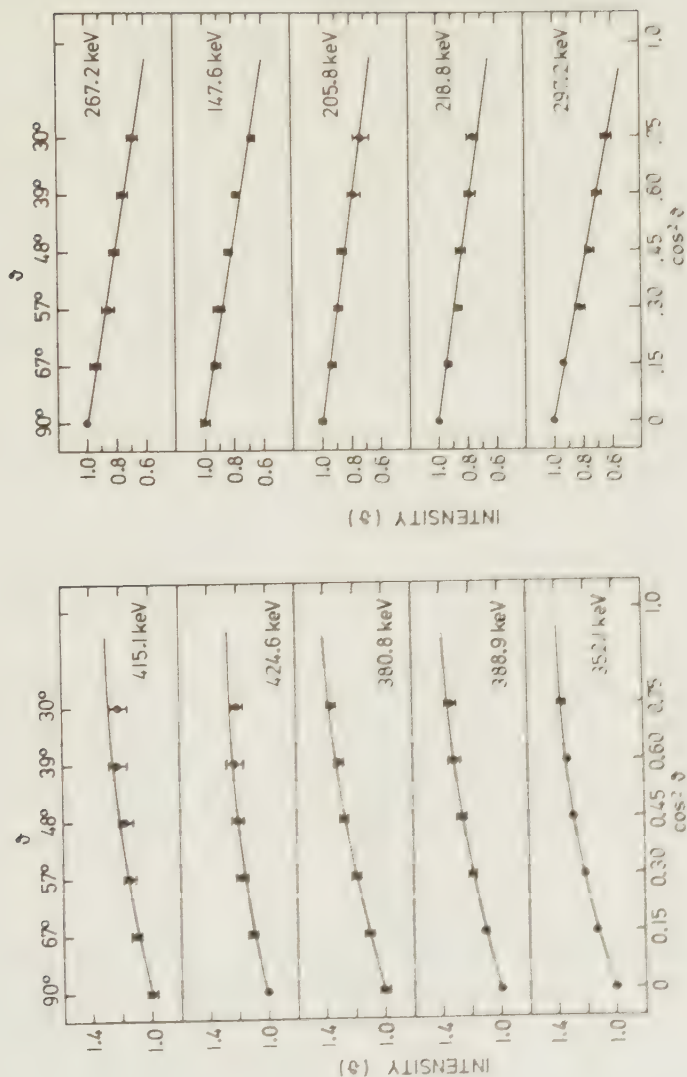


Fig. 11: Experimental angular distribution of some prominent quadrupole and dipole transitions in ^{218}Pa , Fig. 11. a), and b) respectively.

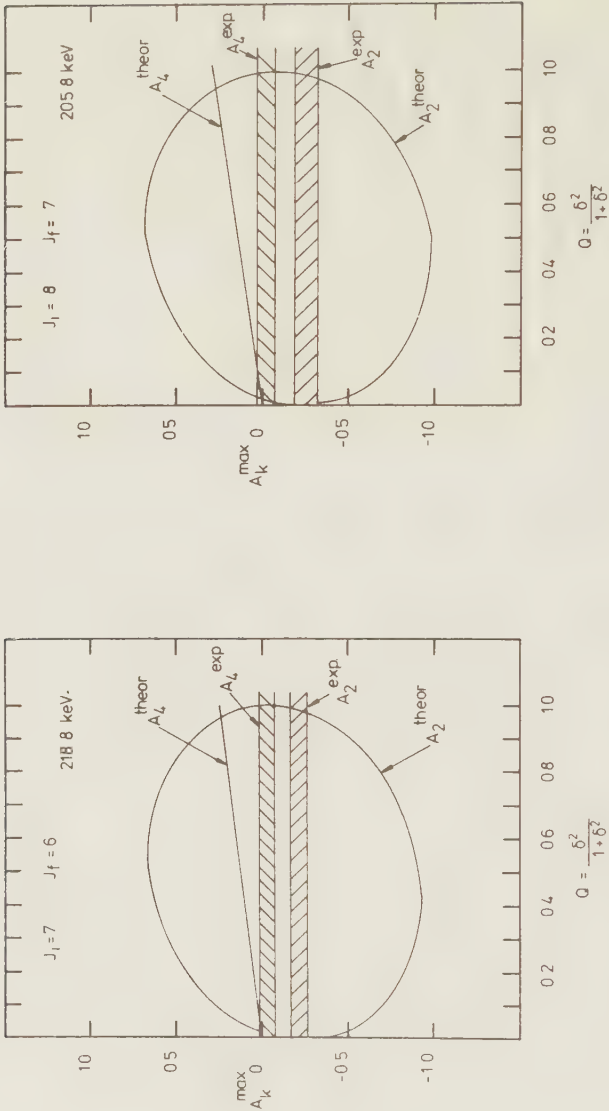


Fig. 12: Arns-Wiedenbecke plots of the coefficients A_2 and A_4 as function of $Q = \frac{\delta^2}{1 + \delta^2}$ for the 218.8 keV and 205.8 keV lines. The A_2^{theor} and A_4^{theor} values were calculated with the computer code ANGDIS.

II.5. The Linear Polarization Experiment

III.5.1. Theoretical Remarks on Polarization and Compton Scattering

As mentioned in Section II.2, there are two methods to determine unambiguously the parity of a transition between two nuclear states, namely the measurement of conversion electrons or the linear polarization of the gamma radiation. A "mini orange" electron spectrometer constructed in this laboratory (see BEH 80) was used to determine the parity of transitions with energies higher than about 500 keV. However, its energy resolution becomes worse for lower energies and, since in ^{218}Ra almost all the transition energies are lower than 400 keV, the parity of the lines was studied by measuring their linear polarization.

The linear polarization experiment measures the number of the gamma-rays with their electric vector in a chosen plane and the number of gamma-rays with their electric vector in a plane perpendicular to the first one. The plane chosen is usually the one containing the quantization axis (i.e. the beam axis) and the direction of the emitted gamma-rays.

The usual way to determine this asymmetry is by means of the polarization sensitivity of the Compton scattering process. The intensity distribution of this process is given by the Klein Nishina formula (KLE 29).

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \times \left(\frac{\hbar\nu'}{\hbar\nu} \right)^2 \times \left\{ \frac{\hbar\nu'}{\hbar\nu} + \frac{\hbar\nu}{\hbar\nu'} - 2 \sin^2 \xi \cos^2 \phi \right\}$$

(III.2.)

where r_0 is the classical radius of the electron, $\hbar\nu$ the incoming photon energy, $\hbar\nu'$ the scattered photon energy, ξ the scattering angle, and ϕ the angle between the polarization plane and the plane spanned by the incoming and the scattered gamma ray (see Fig. 13).

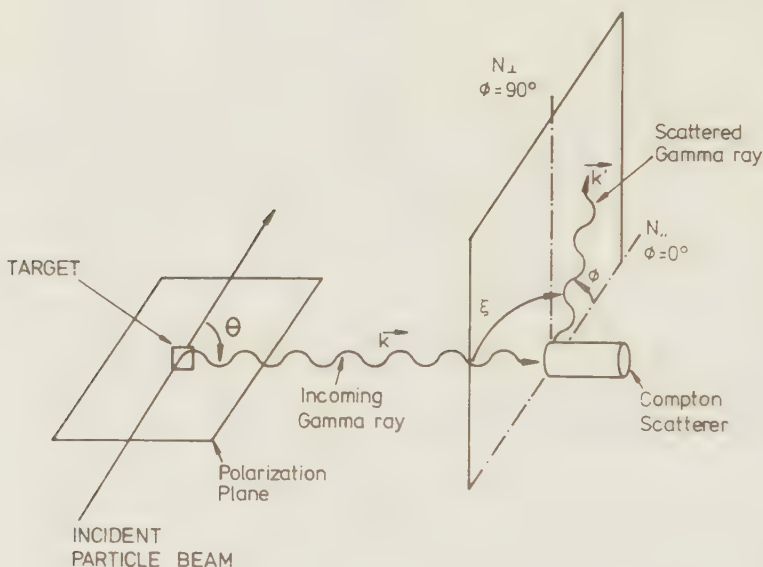


Fig. 13: Illustration of the geometry of a polarimeter based on Compton scattering.

The differential cross section has a maximum at $\phi = 90^\circ$, i.e. in the plane perpendicular to that of the electric vector of the incoming photon. This can be understood classically, considering that the incoming photon induces oscillations of a free electron in the scatterer in a direction parallel to the electric vector and then the oscillating electron emits the scattered photon with a

dipole distribution of intensity.

It is convenient to define the degree of linear polarization of the gamma rays using $I(\theta, \phi=0^\circ)$ and $I(\theta, \phi=90^\circ)$, namely the intensities of gamma rays with their electric vector at an angle ϕ to the plane containing the beam and the incident gamma ray. The definition of linear polarization of the primary gamma rays used in this work follows that of HOO 59:

$$P(\theta, \phi) = \frac{I(\theta, 90^\circ) - I(\theta, 0^\circ)}{I(\theta, 90^\circ) + I(\theta, 0^\circ)} \quad (\text{III.3.})$$

Therefore, the linear polarization P can range, in principle, from +1 (for stretched pure electric transitions), to -1 (for stretched pure magnetic transitions).

The theoretical values of the polarization can be calculated from the angular distribution coefficients A_2 and A_4 (STE 75). For gamma-rays observed at $\theta=90^\circ$ to the beam axis, P is given by the following equations:

$$\text{a) for dipole transitions} \quad P = \pm \frac{3 A_2}{2 - A_2}$$

$$\text{b) for quadrupole transitions} \quad P = \pm \frac{3 A_2 + 1.25 A_4}{2 - A_2 + .75 A_4}$$

The positive sign in these equations is to be associated with multipoles in which there is no parity change (M1 and E2).

In practice, an asymmetry ratio A is measured, which is defined as

$$A = \frac{N_{\perp} - N_{\parallel}}{N_{\perp} + N_{\parallel}} \quad (\text{III.4.})$$

where $N_{\parallel}$ and $N_{\perp}$ are the counting rates registered in the polarization plane and in a plane perpendicular to the first one, respectively.

The experimental value for the linear polarization is then given by

$$P = \frac{A}{Q} \quad (\text{III.5.})$$

where Q is the polarization sensitivity of the polarimeter.

It is customary to express the polarization sensitivity Q in terms of the sensitivity Q_{KN} predicted by the Klein Nishina formula for point detectors:

$$Q_{KN}(\xi, \phi) = \frac{\frac{d\sigma}{d\Omega}(90^\circ, 90^\circ) - \frac{d\sigma}{d\Omega}(90^\circ, 0^\circ)}{\frac{d\sigma}{d\Omega}(90^\circ, 90^\circ) + \frac{d\sigma}{d\Omega}(90^\circ, 0^\circ)} \quad (\text{III.6.})$$

which for a scattering angle $\xi=90^\circ$ takes the value

$$Q_{KN} = \frac{1 + \alpha}{1 + \alpha + \alpha^2}$$

with $\alpha = E / m_0 c^2$.

III.5.2. Description of the Measurement

In principle a polarimeter requires at least two detectors: the scatterer, which defines the direction of the primary gamma ray and in which it is Compton-scattered, and the absorber, which detects the scattered gamma rays at a given angle relative to the plane of polarization. In order to increase the detection efficiency, a polarimeter with four Ge(Li) detectors as absorbers (placed at $\phi=0^\circ$, 90° , 180° and 270°) was constructed, which also gives high energy resolution. The physical characteristics of these four true coaxial detectors are very similar: their crystal geometries are almost identical (about 51.6 mm diameter and 67.5 mm length), their energy resolutions are approximately 2 keV for the 1.33 MeV ^{60}Co line and their efficiencies differ less than 10% from each other.

In the studied ^{218}Ra nucleus, most of the lines fall in an energy range from 130 keV to 450 keV. This implies, according to the relationship between the scattered and the primary photon energies in a Compton process, that energies from about 200 keV down to 40 keV would be deposited in the scatterer detector. It was then possible to use a planar Ge detector as central scatterer.

In this experiment, the polarimeter was placed perpendicular to the beam axis at a distance of 205 mm from the target. The four absorbers were shielded from the primary rays with 100 mm lead.

Fig. 14 shows the electronic setup used in this measurement. For simplicity, the gate generators used to delay and/or to adjust the width of some signals are not included in this picture. The data of this experiment were recorded event by event on magnetic tapes. A five-parameter

1) the electronic circuit was free of dead time (given by the Veto in the Fan In).

2) a coincidence between the scatterer and only one absorber had happened. Coincident events where more than one absorber fired were rejected with the Majority Coincidence unit.

An off line analysis of the data allowed the creation of four spectra (corresponding to $N(\phi=0^\circ)$, $N(\phi=90^\circ)$, $N(\phi=180^\circ)$ and $N(\phi=270^\circ)$) from a digital addition of the energies deposited in the scatterer and in each of the absorbers. These spectra contain events which fall in the prompt peak of the time spectra and which fulfill the kinematic condition for the single Compton scattering. This kinematic condition was calculated by means of the function

$$F = \frac{m_0 c^2 E_s}{E_a (E_s + E_a)}$$

where E_s and E_a are the scatterer and absorber energies and $m_0 c^2$ is the rest mass of the electron.

For normal processes, in which single Compton scattering occurs in the scattered and the outgoing radiation is absorbed in one of the analyzers, the function F is

$$F = 1 - \cos \xi_i$$

whereas for multiple processes $F = \sum_i (1 - \cos \xi_i)$, where ξ_i is the angle of the i th scattering in the scatterer or analyzer. The value of F can be larger than 2 for multiple processes.

In the off-line analysis, the value of F was calculated from the values of E_s and E_a for each event. Hence, by setting a window on the angle ξ (events which lie outside reasonable physical limits of ξ were suppressed), multiple scattering processes were rejected. In this experiment, the width of the window $\Delta\xi$ was 60° .

The fifth column of Table II lists the results of the linear polarization measurements. The spectra corresponding to $\phi=0^\circ$ and $\phi=90^\circ$ are shown in Fig. 15. Almost all the lines are of electric character, with exception of the 310 keV line.

The sensitivity of the polarimeter to the linear polarization Q was calibrated by recording γ -rays transitions of known multipolarity emitted by the ^{134}Cs and ^{192}Ir sources, and with the 380 keV, 389 keV and the 352 keV lines, corresponding to the 6^+ to 4^+ , 4^+ to 2^+ and 2^+ to 0^+ transitions in ^{218}Ra , respectively. It takes a value of $Q=0.83 Q_{KN}$ in the energy range of interest. More details about the performance of this polarimeter can be found in LUT 81.

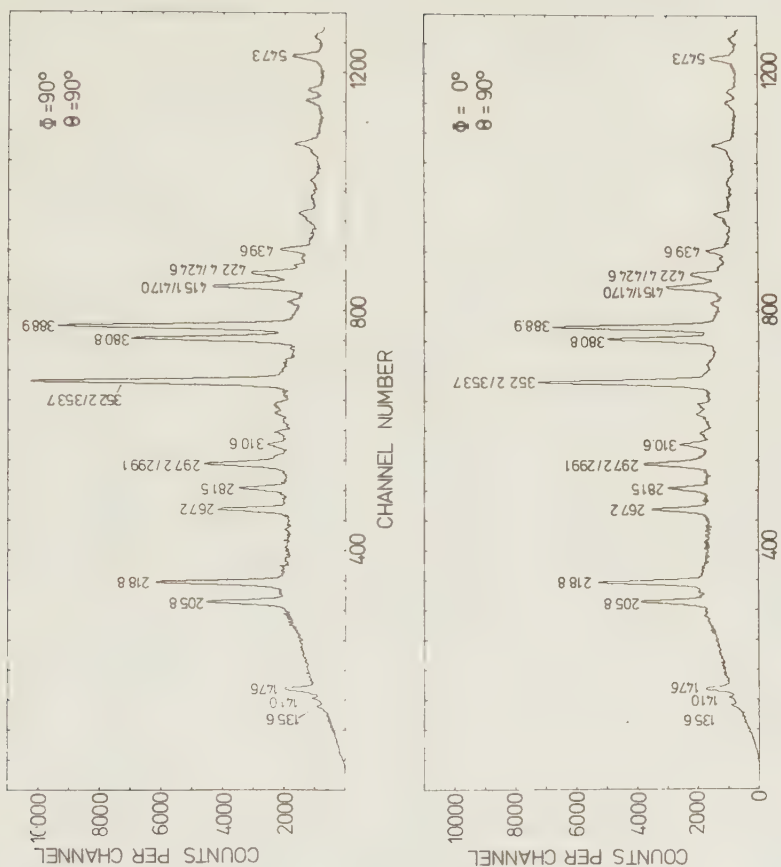


Fig. 15: Gamma-ray spectra corresponding to $\phi=0^\circ$ and $\phi=90^\circ$ showing the electric character of the most of the transitions in ^{218}Ra , with their peak intensities larger at $\phi=90^\circ$ than at $\phi=0^\circ$ and the magnetic character of the 310 keV line (stronger at $\phi=0^\circ$ than at $\phi=90^\circ$).

Table II. Energies, relative intensities, angular distribution coefficients and linear polarizations for the transitions in ^{218}Ra .

Transition energy (keV)	Relative intensity	A_2	A_4	Linear polarization
83.9	25			
135.6	26	-0.22(14)	0.14(19)	0.37(12)
141.0	16	-0.31(12)	0.12(14)	0.31(14)
147.6	88	-0.334(36)	-0.060(71)	0.27(5)
205.8	49	-0.253(77)	0.019(53)	0.26(4)
218.8	75	-0.213(48)	0.036(35)	0.26(3)
267.2	35	-0.324(35)	-0.002(56)	0.28(5)
281.5	28	-0.304(57)	-0.054(68)	0.29(5)
297.2	29	-0.367(27)	0.039(35)	} 0.22(4)
299.1	16	-0.173(54)	0.045(68)	
303.0	5	0.260(65)	-0.116(85)	weak
310.6	10	-0.668(71)	-0.060(82)	-0.24(12)
332.1	9			weak
352.2	100	0.238(17)	-0.094(25)	0.35(4)
353.7	30			
380.8	71	0.244(25)	-0.079(38)	0.39(8)
388.9	100	0.232(26)	-0.079(35)	0.34(8)
415.1	50	0.134(69)	-0.089(77)	} 0.44(8)
417.0	36	0.362(85)	-0.202(97)	
422.4	33	0.260(12)	-0.103(91)	} 0.40(9)
424.6	17	0.108(58)	-0.151(88)	
429.5	7	0.199(66)	-0.053(77)	0.46(21)
434.9	5	0.221(76)	0.042(71)	0.44(28)
439.6	25	0.143(37)	0.08(11)	0.38(11)
547.3	11	0.391(73)	0.045(81)	0.44(8)

The 147.6 keV and 415.1 keV transitions are unresolved doublets. The errors for the energies range from 0.1 keV to 0.3 keV; those for the intensities from 4% to 15% (for the weakest lines).

IV' Experimental Results

IV.1. The Level Scheme of ^{218}Ra

The level scheme of ^{218}Ra was constructed on the basis of the excitation functions, energy combinations, relative transition intensities and coincidence spectra for individual gamma-rays. The ordering of the transitions was established considering that the intensity of transitions occurring above a particular gate decreases in the same manner as in the singles spectrum, while on the other hand all transitions below the stated gate have uniform intensity since side feeding gamma-rays to the lower levels are not in coincidence and thereby do not contribute. The spins and parities were assigned from the angular distribution and linear polarization measurements. The time spectra obtained from pulsed beam measurements do not reveal delayed transitions with $t > 2$ nsec in ^{218}Ra .

It turns out that all prominent lines are consistent either with pure $L=1$ or pure $L=2$ transitions. Furthermore, it is found that in many cases the energies of two $L=1$ transitions add up to those of a third $L=2$ line (see Table II). The linear polarization measurements revealed the electric character of these lines.

The measured transition parities agree with some inferences, which were made from the results of the angular distribution measurement. For example, the small $L=2$ admixture to dipole transitions is a strong indication of their electric character, since the $M1$ transitions appear mostly in competition with the $E2$.

Another hint at their parities was obtained from an analysis of the total rate of the transitions. To determine the true intensity of an electromagnetic decay of a nuclear level, the intensity of the deexcitation via electrons must be added to the γ -intensity obtained from the spectra. This correction is made with the help of the conversion coefficient corresponding to the energy and multipolarity of the considered transition. The coefficients for M1 transitions are greater than those for E1. For instance, the conversion coefficients for a 200 keV gamma energy for electric and magnetic dipole transitions are $\alpha_{E1}=0.09$ and $\alpha_{M1}=2.2$, respectively. Therefore, if strong low energy dipole transitions, such as the 148 keV, 206 keV, 219 keV and 267 keV lines, were of magnetic character, they would be extremely intense, and a reasonable arrangement of these lines in a level scheme would not be possible.

The presence of several doublets, some of them in coincidence with itself, complicated the construction of the level scheme. Table III gives the intensities of three of these doublets (148 keV, 352 keV and 415 keV, see discussion below) and the 389 keV line in the coincidence spectra corresponding to some prominent lines. The coincident spectra generated by setting gates on the 148 keV, 352 keV, 381 keV, 389 keV, 415 keV and 429 keV lines are shown in Fig. 16.

The energy levels obtained in this work and their decay scheme are shown in Fig. 17. The intensities are obtained from the fit to the total projection spectrum of the coincidence matrix, except for cases of overlapping gamma-ray peaks. In each of these special cases, the intensity was determined from the coincident intensities. The level energies were determined by adding up the transition energies corresponding to the strongest lines. A brief summary of the evidence supporting this level scheme is given below:

Table III: Total transition coincidence intensities for the 147.6 keV, 352.3+353.7 keV, 388.9 keV and 415.1 keV lines corresponding to the gates indicated on the left.

E (keV)					
Gate		147.6	352.3	388.9	415.1
147.6		211±10	473±162	389±29	209±36
205.8		440±15	314±110	311±32	183±41
218.8		490±28	673±352	473±18	319±35
267.2		463±12	367±188	267±24	
281.5		265±45	182±37	251±35	141±27
297.2		193±21	218±44	179±36	117±18
380.8		553±44	899±400	602±37	382±69
388.9		700±47	1088±350		487±173
415.1		334±59	683±200	420±45	
417.0		381±20	487±48	378±84	272±37
424.6		205±15	202±54	177±10	126±13
429.5		25±8	53±24	62±10	23±12
547.3		82±11	129±35	83±10	33±9

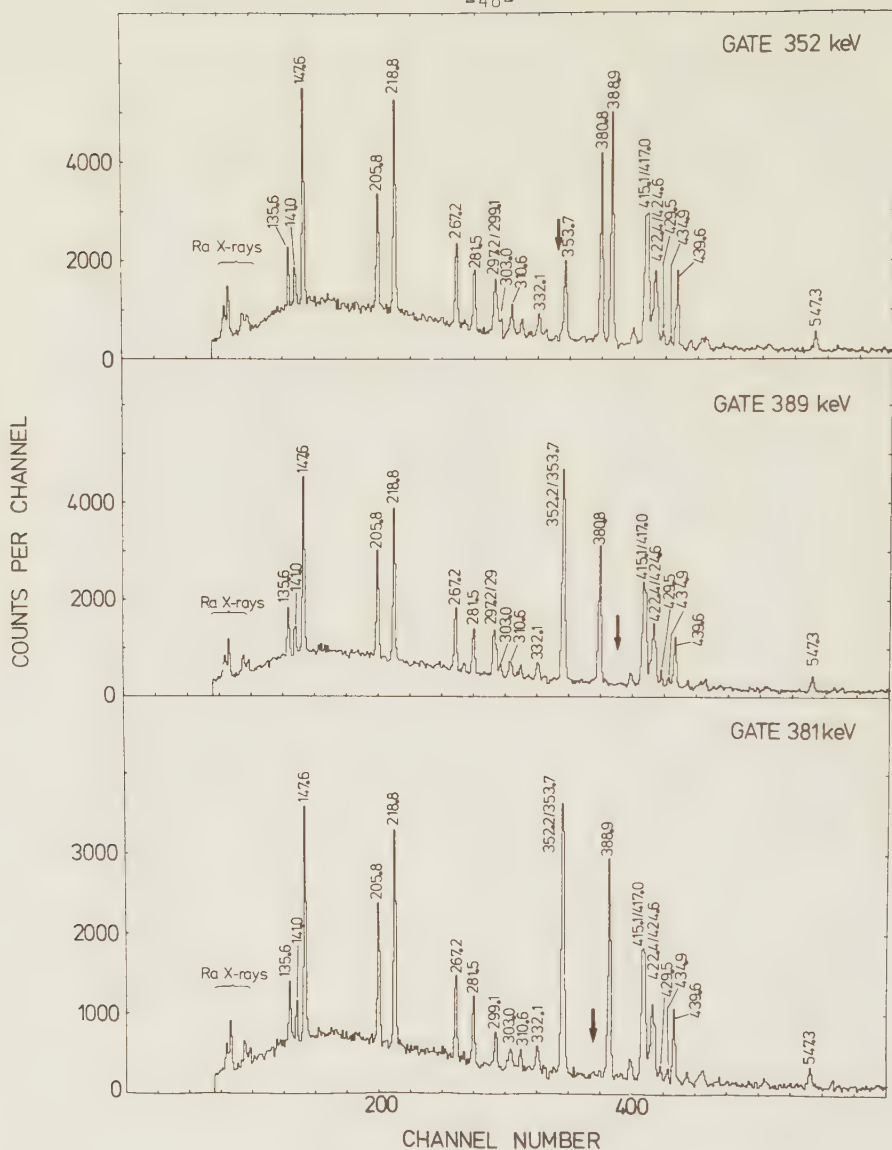
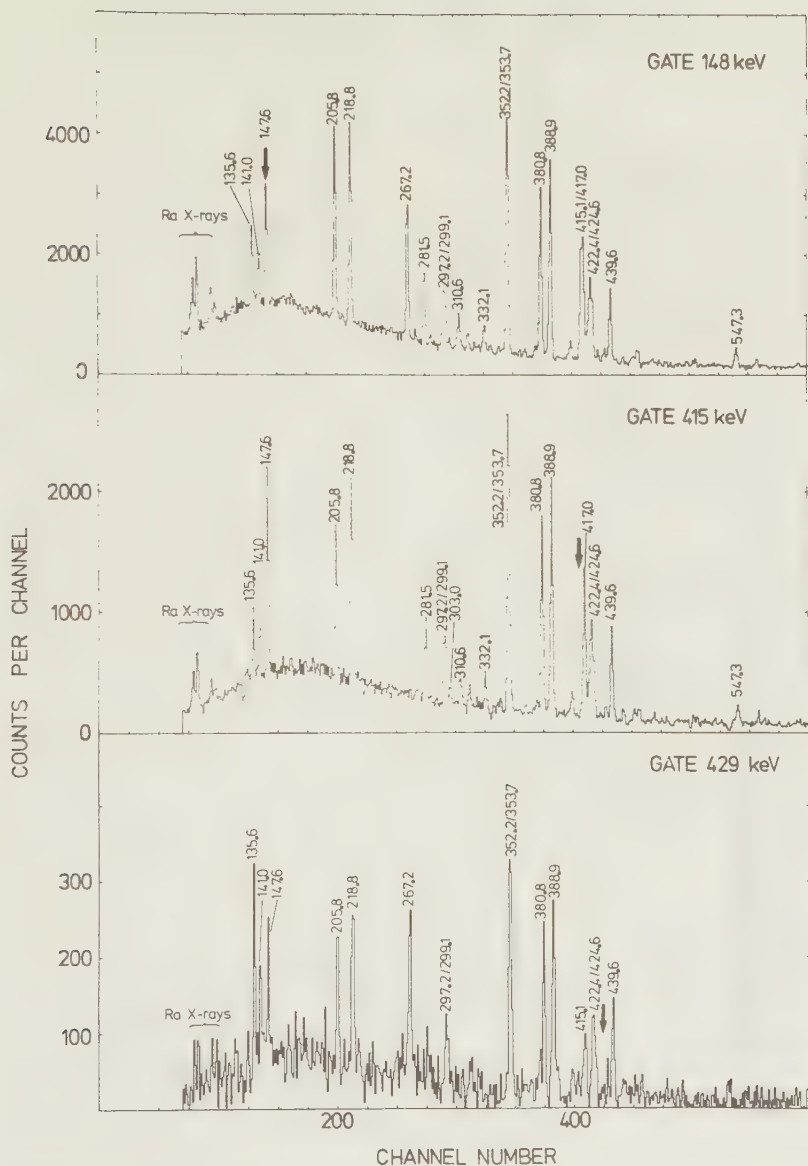


Fig. 16: γ - γ coincident spectra taken with a Ge(Li) detector corresponding to the gating γ -ray energies given for each figure.



(Continued)

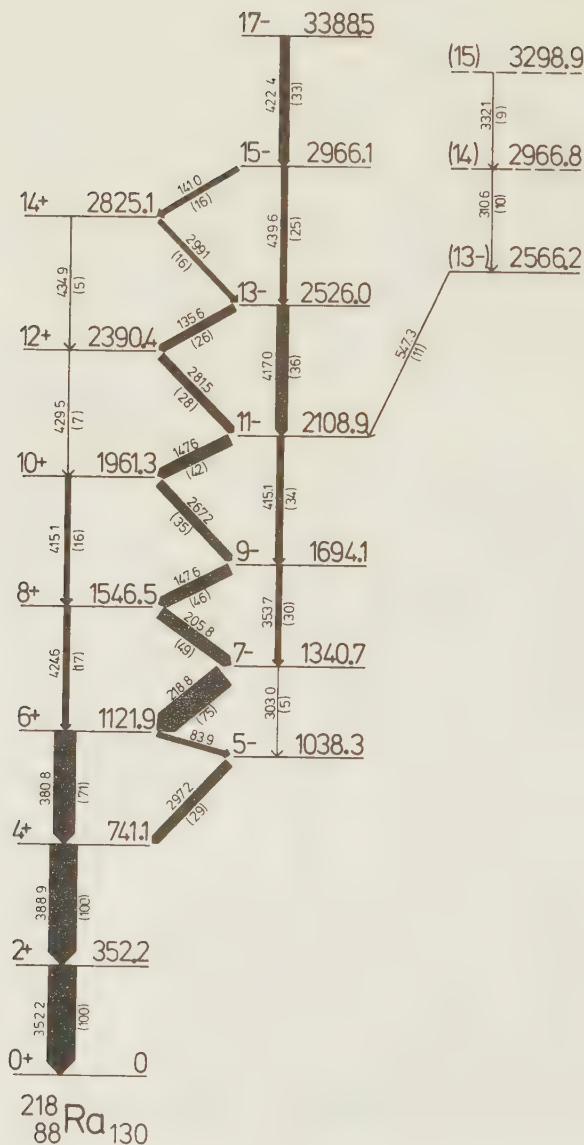


Fig. 17: Level scheme for ^{218}Ra . The energy levels were determined from the energy sum of the strongest transitions. The intensities were normalized to $I(352.2) = 100$.

The $2^+, 4^+, 6^+$ states: The energy sequence of the lower spin states may be established from the excitation function measurements for each line.

If the ratios of the intensity of the cascade members to the intensity of the lowest excited state is plotted versus the bombarding energy, the slopes of the curves increase with the angular momentum of the decaying state. In our case, the ratio of $I_\gamma(352 \text{ keV})$ to the intensities of the other lines suggests the following order for the lower transitions: 352 keV, 389 keV, 381 keV (see Fig. 18).

The 1038 keV level: This state is the lowest observed state of a negative parity band. The parity assignment comes from the electric character of all the interband dipole transitions and the E2 character of the band cascade. The missing coincidence of the 84 keV line with the 381 keV (6^+ to 4^+) transition can be seen clearly in the 381 keV gate generated from the coincidence matrix between the planar detector and one Ge(Li). This is shown in Fig. 19, which also displays the coincident spectra with gates set on the 352 keV and the 389 keV lines. The multipole character of the 84 keV line was deduced from the known multipolarities and parities of the 381 keV and 297 keV lines, because it was not possible to measure its polarization and angular distribution due to the proximity of the 85 keV $\text{Ra-K}\alpha$ line.

The 148 keV doublet: This doublet posed one of the most difficult problems in the construction of the level scheme. From the spectra taken with a planar detector with a resolution of 690 eV at 122 keV and 1 keV stored in 8 channels, it was estimated that the energy difference between these two lines is less than 100 eV.

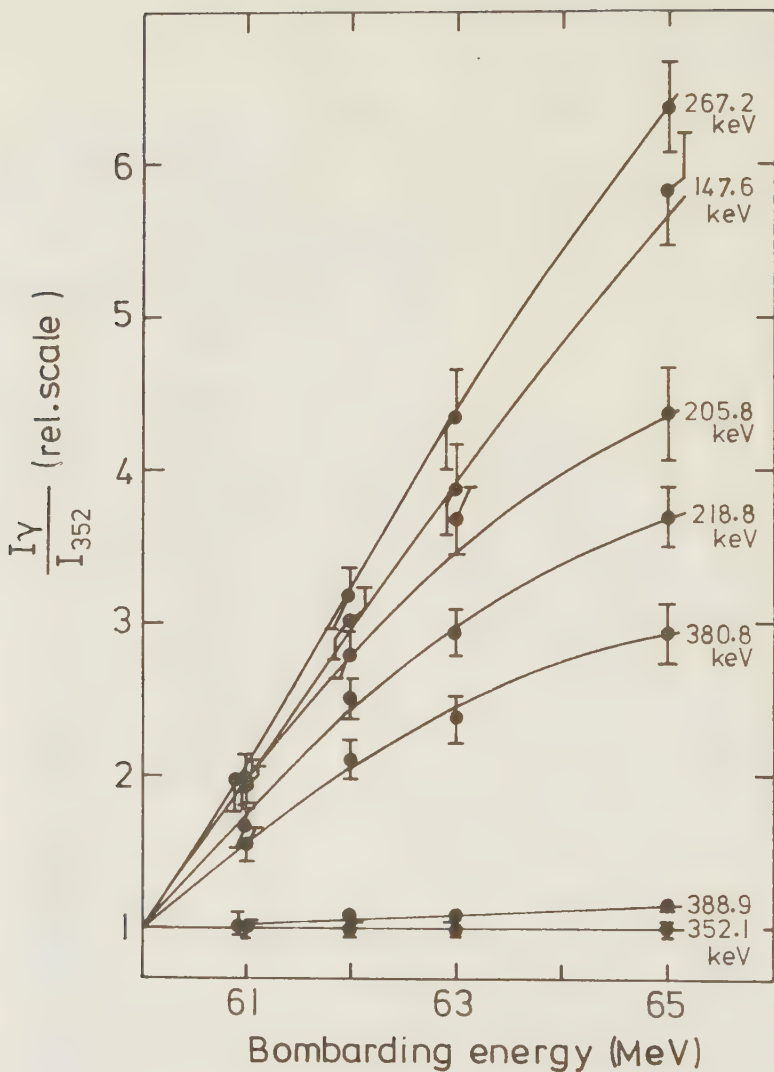


Fig. 18: Excitation functions for some transitions in the $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ reactions produced with bombarding energies $E=60-65$ MeV. The ratio I_γ / I_{352} was normalized to its value at 60 MeV.

COUNTS PER CHANNEL

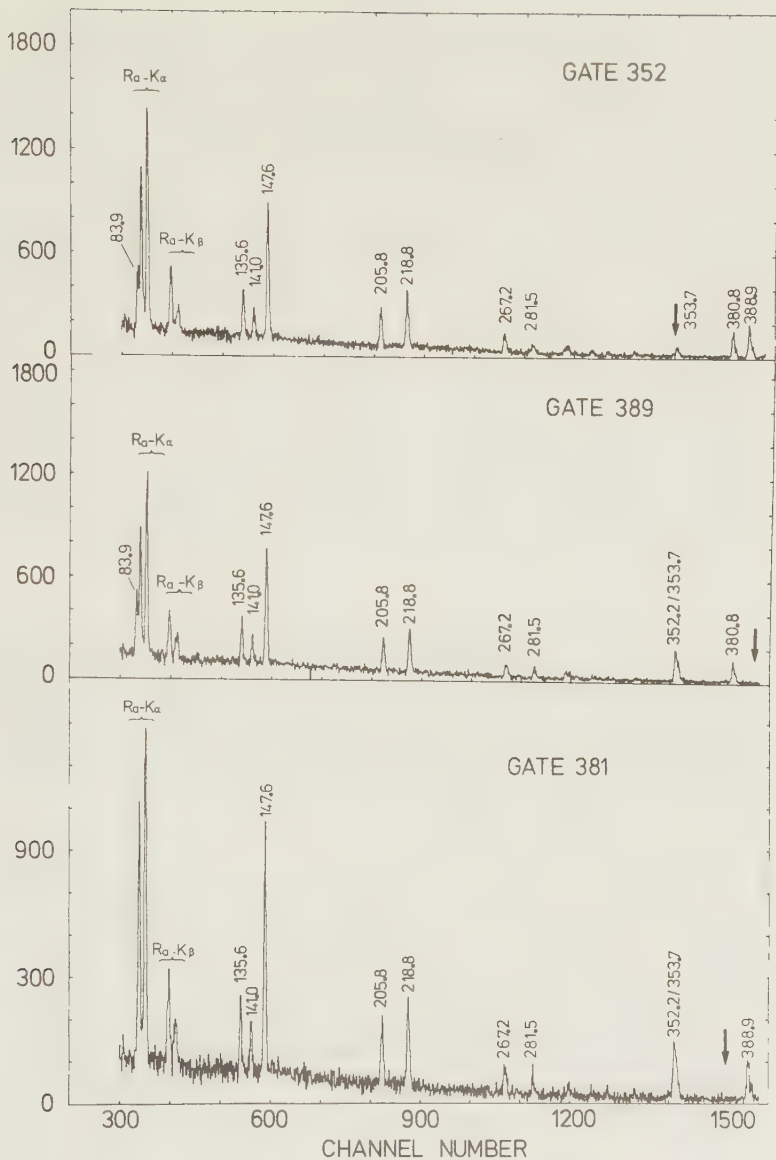


Fig. 19: γ - γ coincidence spectra obtained by gating on the 352 keV, 381 keV and 389 keV lines. The spectra were taken using a planar detector.

A careful background subtraction procedure shows a strong coincidence between them (see Fig. 16). Their location in the level scheme is confirmed with the 429 keV and the 354 keV gate spectra. The assignment of the 267 keV line to the 10^+ to 9^- transition and one of the 148 keV line to the 9^- to 8^+ transition relies on the 354 keV gate spectrum and the systematics of the $B(E2)/B(E1)$ ratios. We shall discuss this point in more detail in Chapter V.

The 415 keV doublet: The 429 keV gate spectrum was the key to the location of the 415 keV doublet, in order to obtain a perfect agreement of the intensity flow in the level scheme (see Fig. 16). The intensities of the 148 keV and 415 keV lines stemming from this gate formed the basis for the intensity assignment to these transitions.

The 2109 keV, 2390 keV, 2526 keV, 2825 keV and 2966 keV levels: These states follow the odd-even staggering starting at the 4^+ state. In each case the dipole transitions are all pure electric ones. The sequence of the E1 interband transitions is established from the missing coincidence with the respective E2 transitions of both bands.

The 2565 keV, 2967 keV and 3299 keV levels: These levels belong to a side band, which is connected to the 2109 keV state of the negative parity band through the 547 keV transition. It was not possible to determine unambiguously the spins and parities of these states because of the weak intensities of the transitions between them. Furthermore, the presence of only one interband transition makes a definite location of these levels difficult.

Regarding the A_2 and A_4 values for the 547.3 keV line, through which the 2565 level is depopulated, only transitions of $I \rightarrow I$, $I \pm 2$ are allowed. (For the $I \rightarrow I-1$ and the $I \rightarrow I+1$ options the computer code ANGDIS yields $A_2 = -.26$, and $A_2 = -.19$, respectively, for $I \rightarrow I-2$ $A_2 = .37$, for $I \rightarrow I+2$ $A_2 = .28$, and for $I \rightarrow I$ $A_2 = .46$, whereas the experimental value is $A_2^{\text{exp}} = .39 \pm .07$). We can therefore only suggest $I^\pi = (13^-)$ for the 2565 keV level, with 11^- or 9^- also being possible.

IV.2. The ^{217}Ra Nucleus

In this section, some inferences on the structure of the odd neighbour ^{217}Ra isotope will be reported, which were obtained simultaneously with study of the ^{218}Ra . As mentioned in the introduction, our knowledge of the ^{217}Ra has until now been limited to the study of the alpha decay of ^{221}Th done by Valli et al. (VAL 70), who have reported the existence of two excited states lying at 330 keV and 755 keV.

The large cross section by the $^{208}\text{Pb}(^{13}\text{C}, 4n)^{217}\text{Ra}$ reaction at beam energies between 70 MeV and 75 MeV shows the convenience of this reaction mechanism for the study of ^{217}Ra . From the excitation functions reported in section II.2., several gamma transitions could be identified as coming from this nucleus. These lines were also observed in the γ - γ coincidence measurements, since the used beam energy ($E_{\text{lab}} = 69$ MeV) allowed the population of excited states in ^{217}Ra . Moreover, an angular distribution measurement at

$E_{\text{lab}} = 74 \text{ MeV}$ was performed, which made possible the investigation of the multipole character of these transitions. In this experiment, the same experimental arrangements as explained in Section III.4. were used.

The data obtained from these measurements are not sufficient to construct a level scheme for ^{217}Ra . However, it is worthwhile to mention some interesting features found in the data analysis.

The gamma-gamma coincidence experiment reveals the existence of some cases, where (as in ^{218}Ra) the energy sum of two coincident lines equals the energy of a third transition, not in coincidence with the first two. In such cases, the angular distribution measurement yields a dipole character for the gamma radiation of the two coincident transitions and a quadrupole character for that of the not coincident line. It furthermore turns out that a band formed with $L=2$ transitions flows almost parallel to this group of lines. With the reasonable assumption that the ground state of this nucleus possesses spin $I=9/2$ (cf. Nilsson diagrams in Chapter V), and that this band is built with stretched quadrupole transitions, levels up to spin $I=25/2$ would be reached.

A search for nanosecond isomerism with the pulsed beam technique established the presence of two isomers in ^{217}Ra , with life times of 14 nsec and 5 nsec, respectively.

The scanty information about ^{217}Ra obtained in this work encourages to pursue investigations in this nucleus.

V Theoretical Discussion

The level scheme of ^{218}Ra displays a characteristic feature, namely the presence of two distinct bands of opposite parities, strongly interconnected. Our discussion will be restricted to these bands, which are also the most relevant ones for the theoretical considerations.

In order to have a notion about the possible single-particle orbits involved in this region, the Nilsson diagrams (taken from LED 78) for protons ($Z > 82$) and neutrons ($N > 126$) are shown in Figs. 20.a and 20.b, respectively. To estimate the deformation of ^{218}Ra (as defined from the E2-transition lifetime) an empirical relation derived by Grodzins (GRO 62) may be used, which holds for all even-even nuclei throughout the nuclear table:

$$E(2^+) \approx \frac{1225}{A^{7/3} \beta^2} \text{ MeV.} \quad (\text{V.1.})$$

This gives a value of the deformation $\beta = 0.11$, suggesting a very transitional behavior of this nucleus. The parameter β is related to the deformation parameter δ , which appears in the Nilsson diagrams, and to first order the relationship is $\delta = 0.95\beta$. According to this estimate, the possible Nilsson single particle orbits in ^{218}Ra are the $g_{9/2}$, $j_{15/2}$ and $i_{11/2}$ for neutrons and the $h_{9/2}$, $i_{13/2}$ and $f_{7/2}$ for protons.

V.1. The Positive Parity Band

Shell-model calculations may provide a useful guideline for the understanding of several features that appear in these bands, but up to now no such calculations have been done in this system. Nevertheless, we can try to identify the dominant components of the neutron and proton configurations by comparison with other Ra isotopes.

Fig. 21 displays the gradual transitions between the even-parity level patterns of these nuclei, from the spherical ^{214}Ra to the deformed ^{228}Ra . The ^{214}Ra nucleus has six protons in addition to the doubly closed ^{208}Pb core. The $\pi(h_{9/2})^6$ configuration determines the energy spacing of its $I^\pi=2^+, 4^+, 6^+$ and 8^+ levels. The shell model picture appears to survive in ^{216}Ra , where the first four excited levels still exhibit a decreasing energy spacing for increasing excitation energies.

In this context, it is illustrative to refer to the ^{212}Po nucleus. It has two protons and two neutrons outside the ^{208}Pb core, and it therefore appears appropriate to study the interaction between proton and neutron pairs in this region. This was described by Auerbach and Talmi (AUE 64), who calculated the spectrum of ^{212}Po using the $\{\pi(h_{9/2})^2, \nu(g_{9/2})^2\}$ configuration. The $I^\pi=0^+, 2^+, 4^+, 6^+$ and 8^+ levels could be reproduced in the $|h_{9/2}^2(I_1); g_{9/2}^2(I_2); I\rangle$ scheme coupling the two protons to $I_1=I$ and the two neutrons to $I_2=0^+$ and vice versa. Hence, it seems possible that the $\{\pi(h_{9/2})^6, \nu(g_{9/2})^2\}$ configuration is the main component in the wave function of the low lying excited states of ^{216}Ra . This admixture of the neutron configuration is responsible for the separation of the energy levels with respect to ^{214}Ra .

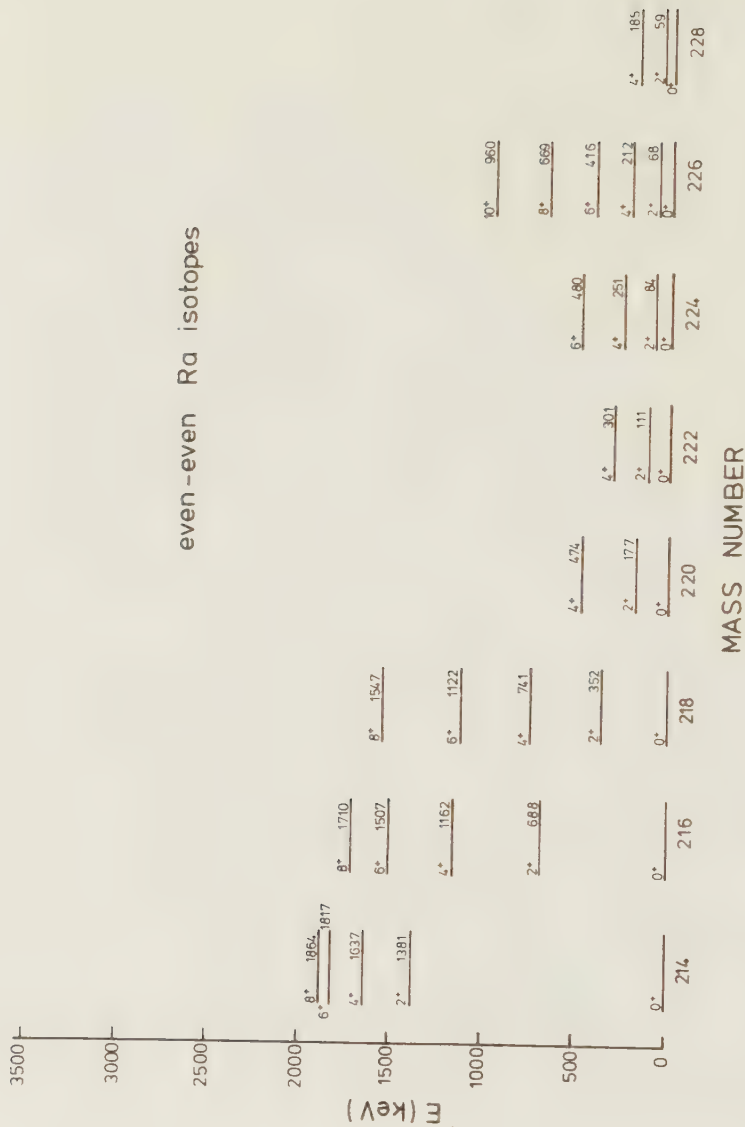


Fig. 21: Members of the low lying even parity states in the Ra isotopes with $126 \leq N \leq 140$. The energy levels for ^{226}Ra are taken from ZIM 80; the other levels are from LED 78.

The presence of four valence neutrons in ^{218}Ra breaks the trend of decreasing energy spacings for increasing spin. The transition energies between the positive-parity states (up to the highest spin observed) are almost equal, with $\Delta E_x \approx 400$ keV. This regularity of the energy spacings indicates a vibrational structure of this band.

As more neutrons are added, the Ra isotopes begin to behave as rotational nuclei. This tendency increases in heavy Ra isotopes, and for example in ^{226}Ra a typical rotational structure can be found, i.e. its energy levels satisfy quite well the $E \propto I(I+1)$ rule.

The equidistant location of the energy levels in ^{218}Ra suggests a collective behavior of this nucleus. Therefore, some qualitative conclusions about the structure of this nucleus can be drawn employing collective nuclear models, such as the variable moment of inertia (VMI) and the interacting boson approximation models (IBA).

In ^{218}Ra the ratio $R_4 = E_4/E_2$, where E_I is the energy of the level with spin I , takes the value of 2.1, i.e. it lies below the value of 2.23, which limits the region of "soft" nuclei (see MAR 68). Such nuclei exhibit the characteristic that even the slightest rotation, e.g. promoting them from the ground state to the first 2^+ state, increase considerably their moment of inertia.

The VMI model reproduces very well the rotational structure of the ground-state band in deformed even-even nuclei. The extension of the VMI model to closed- and near closed- nuclei (MAR 70, SGG 70, GOR 74) stimulated us to try to fit the ground state band of ^{218}Ra on the basis of this model. For states of spin I belonging to the same band, the level energies predicted by the VMI model are given by

$$E_I(J) = \frac{1}{2} C (J - J_0)^2 + \frac{1}{2} \frac{I(I+1)}{J}$$

where J_0 and C are the adjustable parameters. J_0 is the "moment of inertia of the ground state", and the moment of inertia J_I for each state with spin I is determined by the equilibrium condition $\frac{\partial E}{\partial J} = 0$.

The parameters were fitted to reproduce the yrast $I = 2^+$ and 4^+ levels. The result of the fit is compared with the experiment in Fig. 22; the values of the parameter J_0 and the softness $\sigma = 1/2 C J^3$ are -0.0040 keV^{-1} and 0.0287 , respectively. It can be seen that this band can not be well fitted with this model, presenting a downward deviation of energy spacings from the VMI predictions, which indicates a faster rise of the moment of inertia than predicted. The nature of the negative value for J_0 in the "vibrational limit" of VMI is not well understood. Scharff-Goldhaber and Goldhaber (SGG 70) have interpreted this parameter as a measure of the "rigidity" of the spherical ground-state against deformation: The larger the negative value of J_0 , the more firmly the shell structure resists departure from spherical symmetry. In this case $J_{I=0}=0$ and different from J_0 , whereas in the deformed region $J_{I=0}=J_0$.

A more appropriate description of vibration-like patterns is given by a limiting case of the interacting boson approximation model, developed by Iachello, Arima and Feshbach (FES 74, IAC 74, ARI 75, ARI 76). This model gives a description of the bands in terms of a system of interacting bosons, which can be either in a s - ($L=0$) or a d - ($L=2$) state. The Hamiltonian corresponding to this system of s - and d -bosons (considering only two-body interactions and with a fixed number of bosons) can be regarded as a

general rotation in a six dimensional space, and it is possible to determine the eigenvalues of this Hamiltonian using group theoretical methods.

In the case of the vibrational limit, one considers only interacting d-bosons. The five components of the d-boson span a linear vector space which provides a basis for the representation of the group SU(5) (special, or unimodular group of unitary transformations in 5 dimensions). The Hamiltonian corresponding to this limit can be written as

$$H = \sum_{\mu} \epsilon_{\mu} d_{\mu}^{\dagger} d_{\mu} + \sum_{L=0, 2, 4} 1/2 (2L+1)^{1/2} c_L [(d^{\dagger} d^{\dagger})_L (dd)_L]^0 \quad (V.3.)$$

where $d_{\mu}^{\dagger}$ and d_{μ} are the creation and annihilation operators for d-bosons.

The eigenvalues of the interacting d-boson Hamiltonian are

$$E(n_d, \nu, n_{\Delta}, L, M) = \epsilon_2 n_d + \frac{1}{2} \alpha n_d (n_d - 1) + \\ + \beta (n_d - \nu) (n_d + 3 + \nu) + \gamma \{L(L+1) - 6n_d\} \quad (V.4.)$$

where ϵ_2 is the energy of the quadrupole boson, n_d is the boson number, ν is the seniority, namely the number of d-bosons not pairwise coupled to zero angular momentum. n_{Δ} counts boson triplets coupled to zero angular momentum, L is the angular momentum and M is its component along an certain axis. The parameters α , β , γ are related to the parameters c_0 , c_2 , c_4 of (V.3.) by the relations $c_4 = \alpha + 8\gamma$, $c_2 = \alpha - 6\gamma$, $c_0 = \alpha + 10\beta - 12\gamma$. The ground state band (known as the Y band in the literature) is that for which $n_d = \nu = N$, $n_{\Delta} = 0$ and $L = 2N$, and

the energies of the members of this band can be written as

$$\begin{aligned} E(N, N, 0, L=2N) &= 1/8 ((4 \epsilon_2 - 3c_4)L + c_4 L(L+1)) = \\ &= \epsilon_2 N + c_4 \frac{N(N-1)}{2} \quad N = 0, 1, 2, \dots \end{aligned} \quad (V.5.)$$

where ϵ_2 and c_4 are the adjustable parameters.

This model can also produce negative parity states by coupling one octupole 3^- boson, hereafter called f-boson, to quadrupole bosons. This is described by a Hamiltonian of the form

$$H = H_d + H_f + V_{fd} \quad (V.6.)$$

where H_d is the Hamiltonian describing the quadrupole mode (V.3.), H_f is the Hamiltonian describing the octupole mode, and V_{fd} represents the quadrupole-octupole interaction.

In the case in which the states of the d^N configuration to which the f bosons is coupled belong to the ground state band and the total spin I corresponds to the totally aligned value $I=2N+3$ (N band) the eigenvalues of the Hamiltonian are given by

$$E(I=2N+3) = E_Y(L=2N) + \epsilon_3 + N c^{(23)} \quad (V.7.)$$

where $E_Y(L=2N)$ is given by (V.5.) and ϵ_3 and $c^{(23)}$ are adjustable parameters.

A comparison between experimental and theoretical energies of the Y and N bands is shown in Fig. 22. The parameters used are $\epsilon_2=358.07$ keV, $c_4=16.3$ keV, $\epsilon_3=653.43$ keV and $c^{(23)}=-16.67$ keV. We can see that the

positive and the negative parity states of ^{218}Ra are fitted extremely well by the IBA model, which would suggest a collective vibrational structure of these states.

A definite test about the vibrational character of this nucleus would be the observation of the two-phonon states 0^+ and 2^+ at similar excitation energies than the 4^+ . However, in our measurements with (HI, xn) reaction, which is the only way to investigate this nucleus, these states can not be populated since there exist at similar energies higher-spin members of other bands which receive nearly all of the reaction strength.

V.2. The Negative Parity Band

Negative parity bands have been observed both in deformed nuclei (for example, in the actinide ^{236}U (OWE 80) ^{238}U (GRO 75), ^{226}Ra (ZIM 80), and rare-earth ^{162}Er (ZOL 76)) and in transitional nuclei (the even even Pt and Hg isotopes (YAT 74), and the $N=88$ isotones, see BOE 78 and references quoted therein). They are predicted by different models. The most common interpretations are

- i) the octupole vibrational bands
- ii) the two quasi-particle aligned bands

Bohr and Mottelson (BOH 75) discuss the possibility of stable octupole deformations in the ground state or shape isomeric states. Such deformations, if they should happen at all, should occur in the region of the Actinides and hence we have one more possible explanation for the negative-parity states:

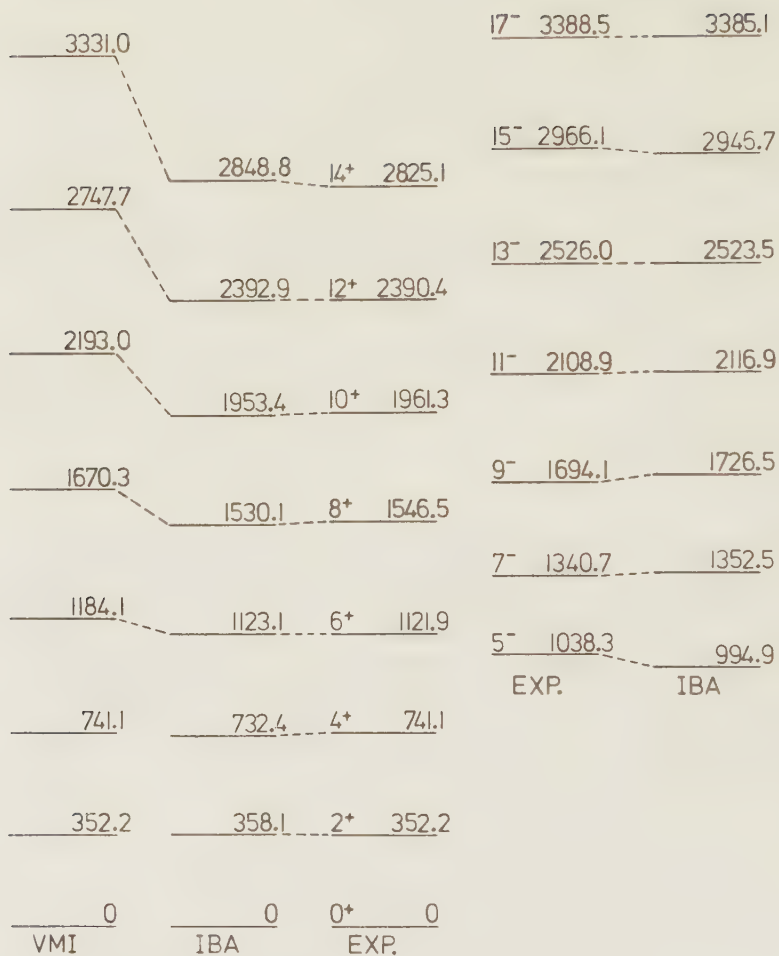


Fig. 22: Comparison between the experimental energy levels and those obtained from the VMI and IBA predictions.

iii) rotational band built onto an stable octupole deformation

The octupole vibration consists of a one phonon excitation, giving rise to a 3^- state in spherical nuclei. In the case of deformed nuclei, the projection of the angular momentum of the octupole vibration on the deformation axis can be $K=0, 1, 2$ or 3 , and rotational bands based on these states can occur. A $K=0$ octupole vibrational band possesses the spin parity sequence $I^\pi=1^-, 3^-, 5^-, \dots$. Bands of this kind were found in deformed actinide nuclei, such as $^{236,238}\text{U}$, ^{232}Th (OWE 80), ^{226}Ra .

Alternatively, negative parity bands in even-even nuclei of the transitional region below ^{208}Pb were interpreted in the framework of the two quasi-particle aligned-band model. In this description, the negative parity states are explained as being built on a two quasi-particle state where one particle moves in a high-spin orbit, whereas the other particle occupies a low spin-orbit with opposite parity. This was first suggested by Neergard and Vogel NEE 70, who found that at the beginning of the rare-earths region the $i_{13/2}$ and $f_{7/2}$ quasineutrons, with their spins coupled antiparallel, contribute with large components to the configurations of the low-lying octupole states. In the transitional region below the double shell-closure ^{208}Pb , the states occupied by the low-spin quasiparticle may be the neutron orbitals $3p_{1/2}$, $3p_{3/2}$ and $2f_{5/2}$, and those of the high-spin quasiparticle in the orbital $1i_{13/2}$, or the analogous proton-configurations may be involved. In this way, one can form $5^-, 7^- \dots$ states as lowest members of a negative parity band if the two particles are coupled such that their spins are antiparallel. Vogel (VOG 76) showed that in the deformed actinide nuclei the negative parity band above a certain critical spin value may change into an aligned two quasiparticle band.

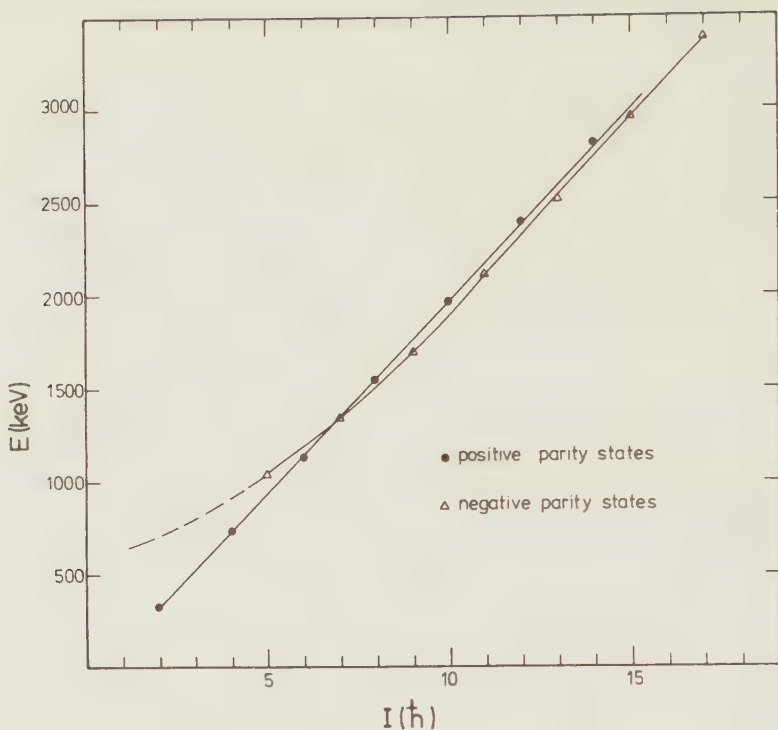


Fig. 23: Excitation energy versus angular momentum diagram corresponding to the positive and negative parity states of ^{218}Ra . A possible extrapolation to $I=1$ and 3 is indicated by a dashed line.

The negative band in ^{218}Ra is formed by levels starting at the $I^\pi=5^-$ state. This band and the even-parity ground-state band are shown in Fig. 23 in an excitation energy vs. angular momentum plot. The available data do not permit to determine unambiguously whether this band is an octupole vibration band or a two-quasiparticle band. For

this isotope there are appropriate Nilsson states (see Fig. 21) available to form the band head of a two-quasiparticle band. However, for a definite assignment one would need more information about the single-particle excitations in the neighbour ^{217}Ra . More precisely, a strong hint in this direction would be the existence of an $i_{13/2}$ decoupled band in this odd nucleus. Bands of this kind were, however, not found in the neighbourhood of ^{218}Ra : negative parity bands in heavier Ra-isotopes were interpreted as $K=0^-$ octupole vibration bands (KUR 77, PEK 81).

The interpretation of the negative parity band in ^{218}Ra as an octupole vibrational band seems to be more plausible in virtue of the following features:

The nuclear shapes for the Ra isotopes with neutron numbers from 126 to 146 were calculated by Moeller, Nilsson and Sheline (MOE 72). While for ^{214}Ra (with closed neutron shell) a rigid, spherical nucleus was predicted, the ^{218}Ra isotope appeared to possess an octupole deformation in its ground state, although there was no quadrupole deformation indicated.

In octupole deformed nuclei in which the potential barrier between one octupole minimum and its mirror image is large enough so as to impede a tunneling motion between these two shapes, nuclear reflection symmetries allow the spin-parity sequence $I^\pi=0^+, 1^-, 2^+, 3^-, 4^+ \dots$

Although the observed levels in ^{218}Ra follow the spin-parity sequence $I^\pi=\text{even}^{\text{even}}, \text{odd}^{\text{odd}}$, the interpretation of their structure in terms of the stable-octupole shape rotor seems to be incorrect. Firstly, for a stable rotating octupole deformation the even- and odd- spin fuse into one band, with the usual $I(I+1)$ energy spacing, giving rise to the relation

$$\frac{E_{I+3} - E_{I+1}}{E_I - E_{I-2}} \rightarrow \frac{2I + 5}{2I - 1} \quad (\text{V.8.})$$

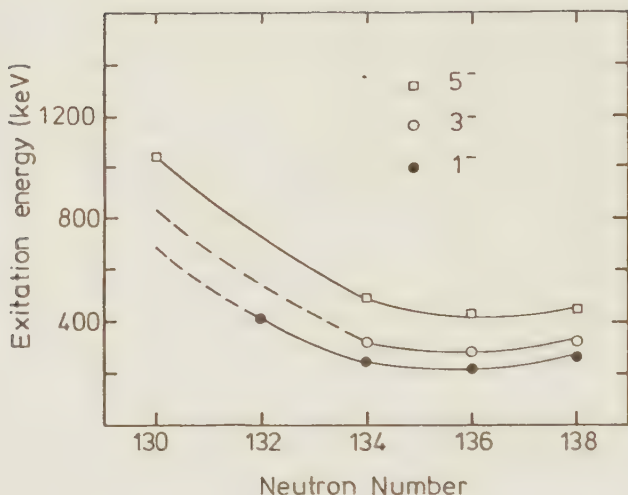


Fig. 24: Systematics of the low lying negative parity states in the Ra isotopes. The energy values corresponding to the Ra isotopes ($N \geq 132$) were taken from LED 78. Extrapolations of the 1^- and 3^- states to $A=218$ ($N=130$) are indicated with dashed lines.

which is not fulfilled in the case of ^{218}Ra . Secondly, the extrapolations to a probable 1^- level in ^{218}Ra (see Figs. 23 and 24) indicate that this state would have an excitation energy around 600 keV. This means that this level would lie between the 2^+ and 4^+ states. This feature and a probable location of the 3^- level beyond the 4^+ state (cf. Figs. 23 and 24) would suggest the presence of two bands with opposite parity $I^\pi = 0^+, 2^+, 4^+$ and $I^\pi = 1^-, 3^-, 5^-$, where the odd spin band is displaced upward in energy with respect to the

even spin band. This energy shift between these two bands is understood as stemming from a tunneling motion between the mirror shapes (see BOH 75, pages 17,18).

Fig. 25 shows the experimental ratios of transition energies (V.8.) for ^{226}Ra and ^{218}Ra . It can be seen that this ratio converges rapidly to unity in ^{218}Ra , although, on the contrary as in ^{226}Ra , this relation tends to unity from below. The convergence of this relation to one is interpreted as an alignment of the vibrational angular-momentum of the octupole band along the rotation axis caused by the Coriolis force when the rotation-vibration interaction is weak (GRO 75). The rotor-aligned vibrator produces a band with energy spacings similar to those of the ground band, but having spins $3\hbar$ higher. For this reason the energies of the transitions $I \rightarrow (I-2)$ and $(I+3) \rightarrow (I+1)$ are quite similar. Precisely this behavior was the one assumed in the calculation of the negative-parity levels in the IBA model.

As indicated by the extrapolations made in Figs. 23 and 24, the 1^- and 3^- states lie probably higher than the 2^+ and 4^+ states of the ground state band, respectively. This, and the abrupt fall-off in the intensity flow of the 7^- to 5^- transition (hinting that the 5^- to 3^- transition is even less intense) impede the observation of the 1^- and 3^- levels in our investigation with (HI, xn) reactions. It is, however, worth notating that in ^{218}Ra a 3^- level could lie lower in energy than the first 1^- level, as in the case of the spherical even-even Sm isotopes (BOH 75, page 577). This also possible feature does not contradict the above interpretation of the negative-parity band as an octupole vibrational one.

The search for such low odd-spin states remains a challenging experimental problem. Such states are usually populated in alpha decay, but investigations of Valli

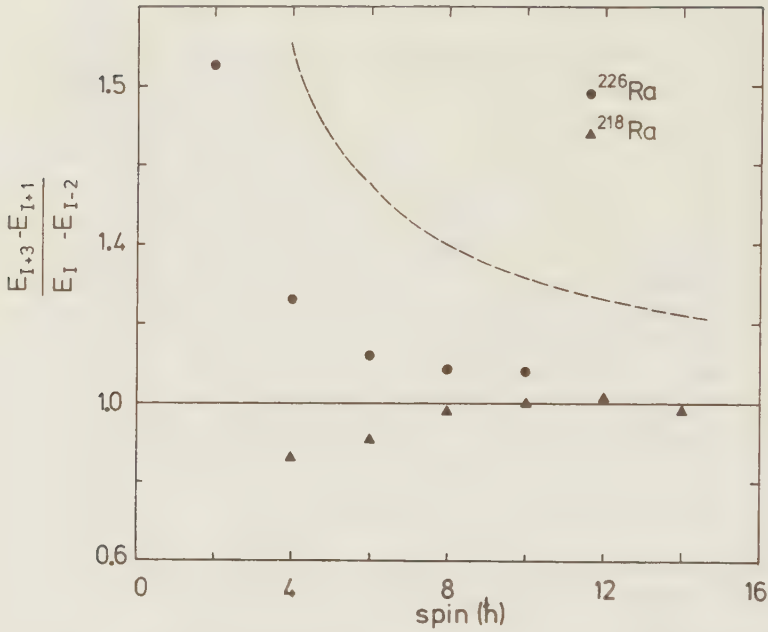


Fig. 25: Experimental ratios of transition energies within the octupole band to transition in the ground-state band in ^{226}Ra (circles) and ^{218}Ra (triangles). This figure also shows the predicted behavior for an aligned-vibrator (solid line) and for a stable rotor (dashed line).

(VAL 70) and Torgerson (TOR 70) on the α -particle decay of ^{222}Th indicate that this nucleus deexcites directly to the ground state of ^{218}Ra .

V.3. Matrix Elements

The electromagnetic transition probabilities deexciting nuclear states provide a very direct way of obtaining information about the nuclear structure since the matrix elements of the multipole operators depend on the amplitudes and phases of the wave functions of the nuclear states involved. The reduced matrix element $B(E\lambda; I_i \rightarrow I_f)$ of an electric λ -pole transition from a nuclear state I_i to a final nuclear state I_f can be expressed as

$$B(E\lambda; I_i \rightarrow I_f) = \frac{\lambda((2\lambda+1)!!)^2 \hbar (\hbar c)^{2\lambda+1} T(\lambda)}{8\pi (\lambda+1) E_\gamma^{2\lambda+1}} \quad (V.9.)$$

where $T(\lambda)$ is the transition probability per unit time for the emission of a photon of energy E and angular momentum λ (DAV 68). The transition probability T is equal to $1/\tau$, where τ is the lifetime of the nuclear state. Therefore, if a transition has only one decay channel, knowledge of its lifetime enables one to determine the absolute value of the matrix element. (In the case of a mixed transition, the mixing ratio δ is also necessary).

It is common to express the actual $B(E\lambda)$ - and $B(M\lambda)$ -values in Weisskopf units, which provide a rough estimate for a single particle transition probability for each multipolarity (WEI 51). The Weisskopf estimate for electric dipole and quadrupole transitions in ^{218}Ra are

$$\begin{aligned} B_W(E1; I_i \rightarrow I_f) &= 0.0645 A^{2/3} e^2 \text{fm}^2 = 2.33 e^2 \text{fm}^2 \\ B_W(E2; I_i \rightarrow I_f) &= 0.0594 A^{4/3} e^2 \text{fm}^4 = 77.9 e^2 \text{fm}^4. \end{aligned} \quad (V.10.)$$

It would be very attractive to have absolute values of the $B(E2)$ coefficients for the even-spin and odd-spin $L=2$ cascades in ^{218}Ra . However, it was not possible to perform lifetime measurements in the subnanosecond region. From the delayed-coincidence measurements it was known that the lifetime of the transitions are smaller as 2 nsec. With this value of the half-life we can give a lower limit for $B(E2)$, $B(E2; 2^+ \rightarrow 0^+) > 3 B(E2)_W$.

Systematics of $B(E2; 2^+ \rightarrow 0^+)$ values in this region of the nuclei chart, see for example the compilations by Stelson and Grodzins (STE 65), allow us to estimate a value $B(E2) \approx 10 B(E2)_W$. This estimate agrees roughly with a calculation of $B(E2)$ done on the basis of the Grodzins relation (V.1.), which predicted for ^{218}Ra a value $B(E2) = 30 B(E2)_W$.

An interesting feature in ^{218}Ra is the presence of strong interband $E1$ -transitions. These transitions deexcite not only the negative parity band but also the positive parity band, competing in both bands with the $E2$ transitions. It is a striking feature that the $B(E\lambda)$ ratios

$$\frac{B(E1)}{B(E2)} = \frac{I(E1) E(E2)^5}{I(E2) E(E1)^3} \times 0.86 \times 10^{-6} \text{ fm}^{-2}$$

for the de-excitation of the negative and positive-parity states remain almost constant (see Table IV). In this expression $I(E\lambda)$ is the intensity of the λ -pole transition and $E(E\lambda)$ is the corresponding gamma energy, given in MeV. The constancy of the $B(E\lambda)$ ratios for all spins may suggest a similar structure within the bands and also perhaps a similar structure of both bands.

On the basis of the estimates of the $B(E2)$ -value corresponding to the $2^+ \rightarrow 0^+$ transition one can calculate the order of magnitude of the hindrance factor of the $E1$ -transitions relative to the Weisskopf estimate. Assuming an average value $B(E2) = 20 B(E2)_W$, the hindrance obtained is about 10^{-3} , in reasonable agreement with the systematic trend in these nuclei (PER 66, KUR 77). The not exceedingly large retardation factor of the $E1$ transitions between the two bands would indicate that in this nucleus the shape isomerism is not likely. This agrees with a recent study of Peker et al. (PEK 81), who ruled out the existence of a possible octupole deformation on $K^\pi = 0^-$; $I = 1^-$ states in even Ra and Rn isotopes with $A \approx 218$.

From the retardation of the $E1$ transitions one can not infer whether the states are collective levels or not (PEK 79). The observation of strong $E3$ transitions would provide evidence for the collective nature of octupole vibrational states. In this work, because of the odd-even staggering of the spins, the competition of the $E1$ transitions impeded the observation of any $E3$ transitions.

Table IV: $B(E1)/B(E2)$ ratios corresponding to the deexcitation of levels in ^{218}Ra .

Level Energy (keV)	I^π	$B(E1)/B(E2)$ ($\times 10^{-6} \text{ fm}^{-2}$)
1121.9	6^+	4.1 ± 1.0
1340.7	7^-	3.1 ± 0.6
1546.5	8^+	3.9 ± 0.8
1694.1	9^-	2.3 ± 0.8
1961.3	10^+	1.2 ± 0.4
2108.9	11^-	4.0 ± 1.4
2390.4	12^+	2.2 ± 0.8
2526.0	13^-	3.1 ± 1.0
2825.1	14^+	1.6 ± 0.4
2966.1	15^-	3.2 ± 0.7

VI Conclusions

The present work is a study of levels of ^{218}Ra populated by the $^{208}\text{Pb}(^{13}\text{C}, 3n)^{218}\text{Ra}$ reaction. The level scheme of ^{218}Ra , previously unknown, has been established up to spin $I^\pi=17^-$. The excited levels can be grouped into two bands, one with positive parity and the other with negative parity. The configurations of these levels remain an open question, since no shell-model calculations have been performed for ^{218}Ra .

The regularity of the energy spacings, more accentuated in the positive parity band, suggests a vibrational behavior of this nucleus. A comparison of the even-spin states with those in other even-even Ra isotopes shows clearly the transitional character of ^{218}Ra . The negative parity band, which starts at spin $I=5$, has been interpreted as an octupole vibrational band. Such a band was also observed in heavier Ra isotopes. The presence of strong interband E1 transitions deexciting both bands is one of the striking features in the level scheme of ^{218}Ra . Although the strengths of these transitions has not been measured, their hindrance factor was estimated to be 10^{-3} . This small hindrance of the E1 transitions rules out the idea of shape isomerism in this isotope.

Based on this research, further experimental work in this transitional region seems worthwhile. In particular, it is of great interest to search for the negative low-lying spin-states $I^\pi=1^-$ and 3^- . This would help in understanding the nature of the negative-parity band.

The $^{13,14}\text{C}$ beams available at the Munich tandem accelerator enable the study of a wider range of Ra isotope through (HI, xn) reactions. Information concerning the single particle excitations in the odd $^{215,217,219}\text{Ra}$ isotopes would contribute substantially to the comprehension of the level structure in this region. We are therefore engaged in the study of ^{217}Ra , and the construction of its level scheme is in progress. Finally, it is hoped that this investigation may stimulate theoretical calculations for these nuclei in order to make quantitative comparisons possible for ^{218}Ra .

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